Advanced Modeling & Simulation (AMS) Seminar Series

Numerical Simulation of Bolide Entry with Ground Footprint Prediction

Michael J. Aftosmis

NASA Ames Research Center, Moffett Field, CA

Marian Nemec

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Donovan L. Mathias

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Marsha J. Berger

Courant Institute, NYU, NY, NY

4 February, 2016, NASA Ames

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AIAA Paper 2016-0998

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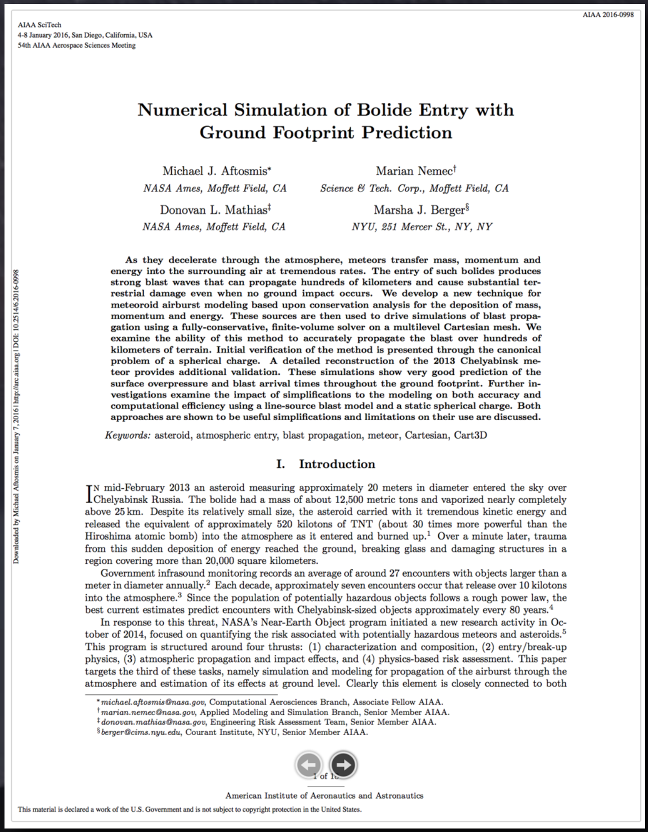

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Marian Nemec†
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Donovan L. Mathias‡
NASA Ames, Moffett Field, CA

Marsha J. Berger§
NYU, 251 Mercer St., NY, NY

As they decelerate through the atmosphere, meteors transfer mass, momentum and energy into the surrounding air at tremendous rates. The entry of such bolides produces strong blast waves that can propagate hundreds of kilometers and cause substantial terrestrial damage even when no ground impact occurs. We develop a new technique for meteoroid airburst modeling based upon conservation analysis for the deposition of mass, momentum and energy. These sources are then used to drive simulations of blast propagation using a fully-conservative, finite-volume solver on a multilevel Cartesian mesh. We examine the ability of this method to accurately propagate the blast over hundreds of kilometers of terrain. Initial verification of the method is presented through the canonical problem of a spherical charge. A detailed reconstruction of the 2013 Chelyabinsk meteor provides additional validation. These simulations show very good prediction of the surface overpressure and blast arrival times throughout the ground footprint. Further investigations examine the impact of simplifications to the modeling on both accuracy and computational efficiency using a line-source blast model and a static spherical charge. Both approaches are shown to be useful simplifications and limitations on their use are discussed.

Keywords: asteroid, atmospheric entry, blast propagation, meteor, Cartesian, Cart3D

I. Introduction

In mid-February 2013 an asteroid measuring approximately 20 meters in diameter entered the sky over Chelyabinsk Russia. The bolide had a mass of about 12,500 metric tons and vaporized nearly completely above 25 km. Despite its relatively small size, the asteroid carried with it tremendous kinetic energy and released the equivalent of approximately 520 kilotons of TNT (about 30 times more powerful than the Hiroshima atomic bomb) into the atmosphere as it entered and burned up.[1] Over a minute later, trauma from this sudden deposition of energy reached the ground, breaking glass and damaging structures in a region covering more than 20,000 square kilometers.

Government infrasound monitoring records an average of around 27 encounters with objects larger than a meter in diameter annually.[2] Each decade, approximately seven encounters occur that release over 10 kilotons into the atmosphere.[3] Since the population of potentially hazardous objects follows a rough power law, the best current estimates predict encounters with Chelyabinsk-sized objects approximately every 80 years.[4]

In response to this threat, NASA's Near-Earth Object program initiated a new research activity in October of 2014, focused on quantifying the risk associated with potentially hazardous meteors and asteroids.[5] This program is structured around four thrusts: (1) characterization and composition, (2) entry/break-up physics, (3) atmospheric propagation and impact effects, and (4) physics-based risk assessment. This paper targets the third of these tasks, namely simulation and modeling for propagation of the airburst through the atmosphere and estimation of its effects at ground level. Clearly this element is closely connected to both

* *michael.aftosmis@nasa.gov*, Computational Aerosciences Branch, Associate Fellow AIAA.
† *marian.nemec@nasa.gov*, Applied Modeling and Simulation Branch, Senior Member AIAA.
‡ *donovan.mathias@nasa.gov*, Engineering Risk Assessment Team, Senior Member AIAA.
§ *berger@cims.nyu.edu*, Courant Institute, NYU, Senior Member AIAA.

4 February, 2016, NASA Ames

Asteroid Threat Assessment Project

Chelyabinsk, Russia, February 2013

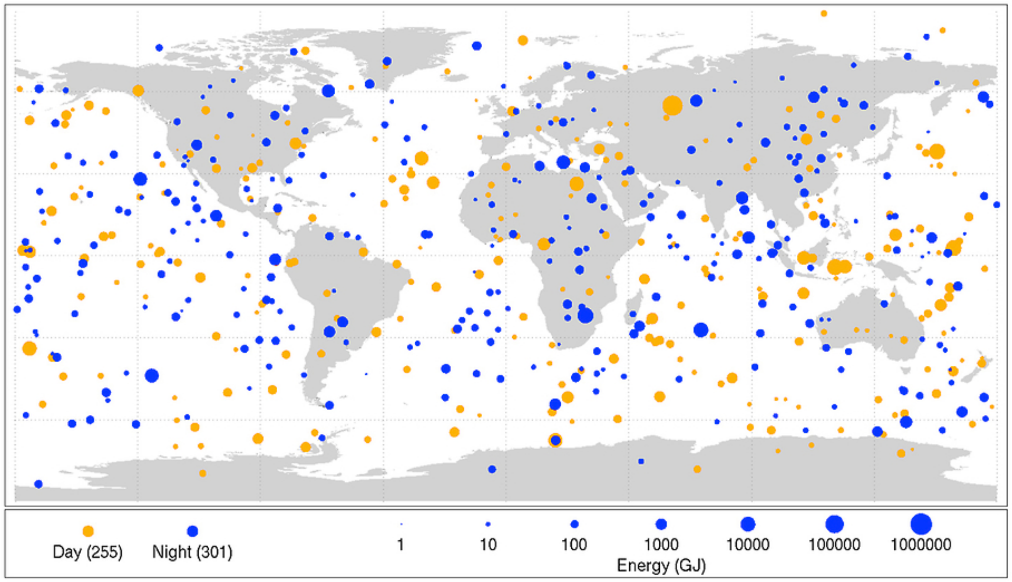
Asteroid Threat Assessment Project

Chelyabinsk, Russia, February 2013

- Entry speed: ~20km/sec
- Energy: ~520 kilotons of TNT (2.2 x 10^{15}joules)
- Energy equivalent to magnitude 7.0 earthquake
- Damage to ~7300 structures over 20,000 km^2

Asteroid Threat Assessment Project

- Earth is bombarded by relatively energetic objects with disturbing regularity



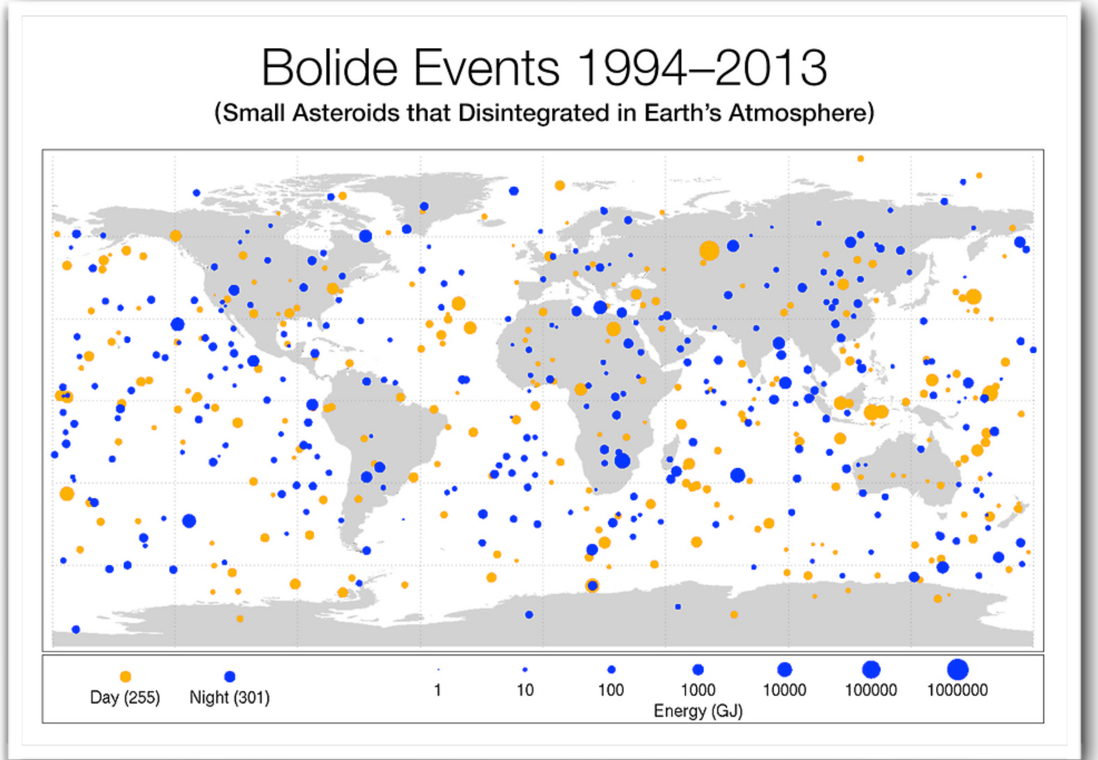
http://neo.jpl.nasa.gov/news/news186.html

Asteroid Threat Assessment Project

- Earth is bombarded by relatively energetic objects with disturbing regularity

- ATAP project began in Oct 2014

- Seeks to provide quantitative risk assessment for particular near earth objects



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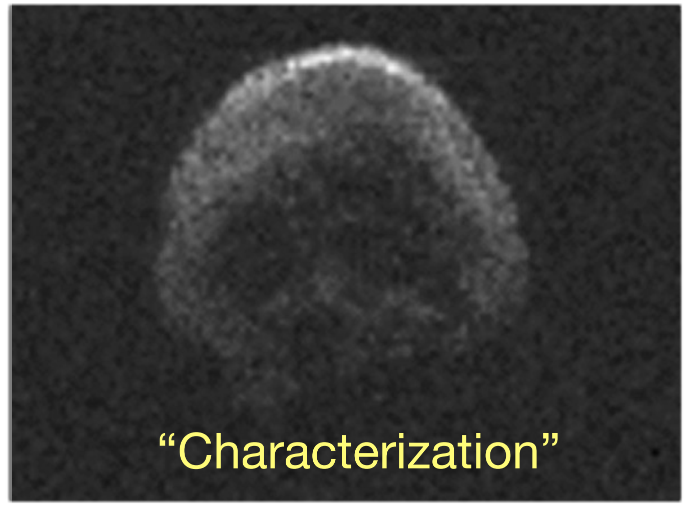
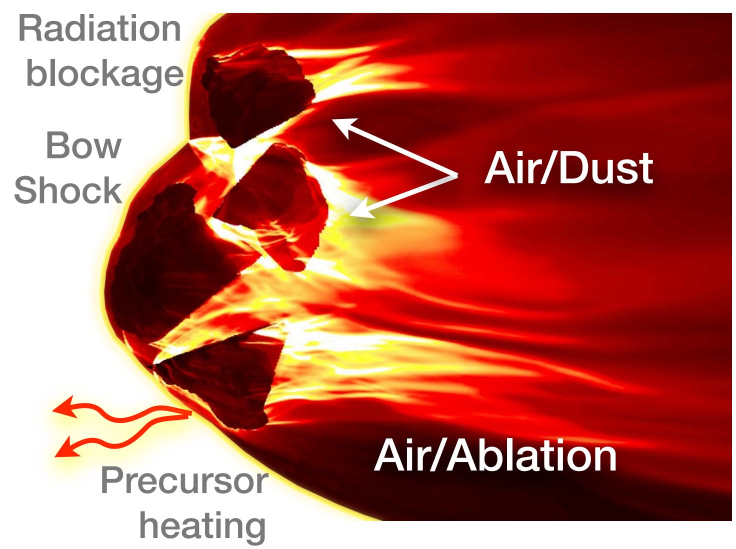


Entry Physics



ATAP Elements

1. Characterization
2. Entry physics
3. Propagation to ground
4. Physics-based risk analysis

Asteroid Threat Assessment Project

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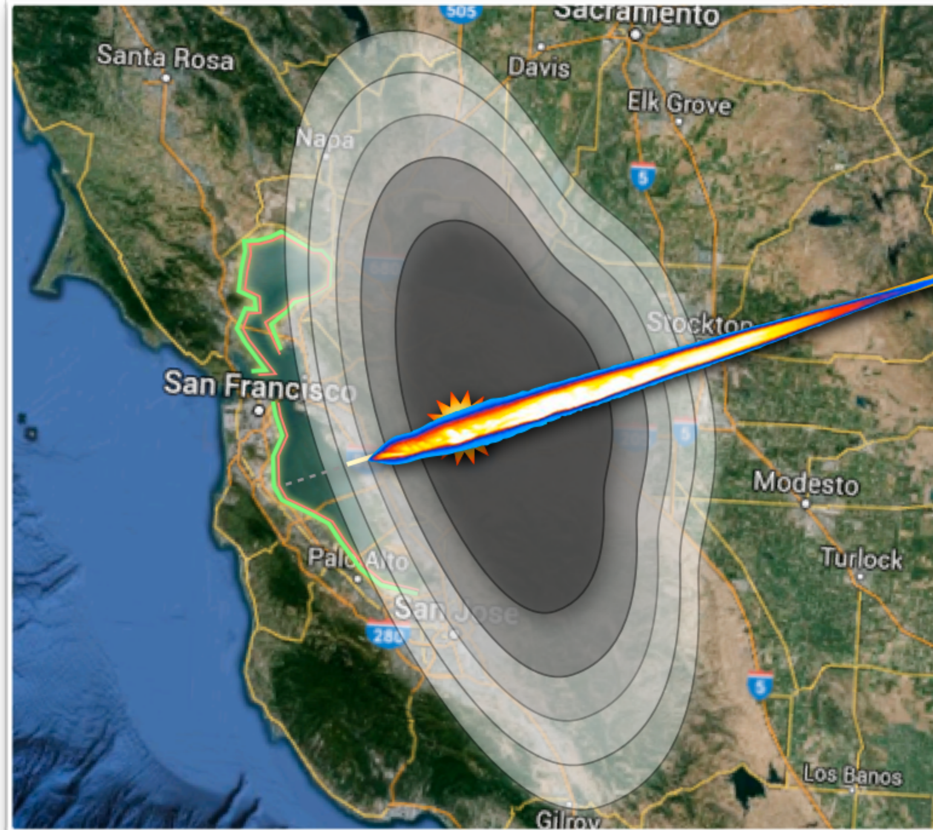


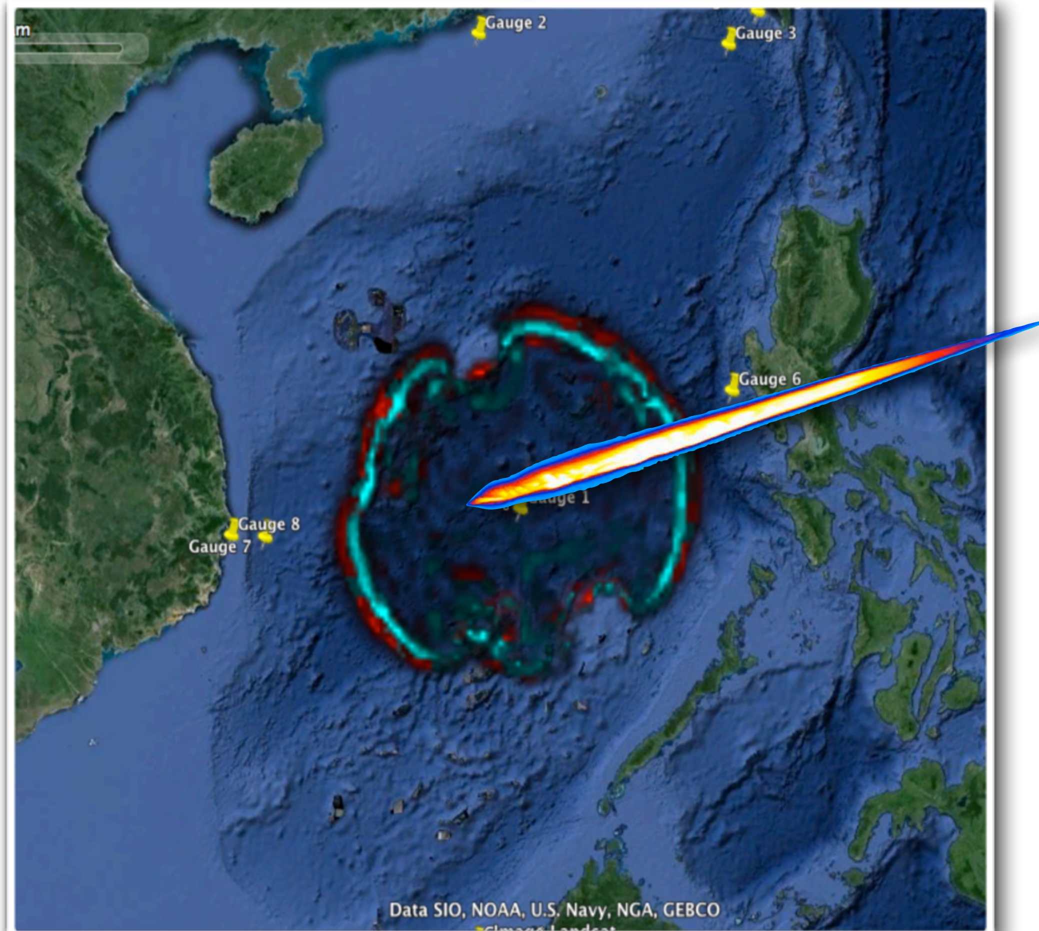
Goal is prediction of surface footprint

- Far-field propagation drives surface overpressure, wind & tsunami
- These are the **key inputs** for ground damage & casualty prediction
- Goal is to be able to vary entry inputs parametrically to understand main sensitivity drivers of the ground footprint for Physics-based Risk Analysis (PRA)

Overview

Report current status of effort and connection with PRA and tsunami

- Modeling tools & solver
- Entry & airburst modeling
  - Energy deposition model
  - Chelyabinsk Case Study
- Ground-footprint sensitivity
  - Line-source vs time-dependent
  - Entry angle & spherical blast
- Upcoming Efforts
  - Tsunami prediction



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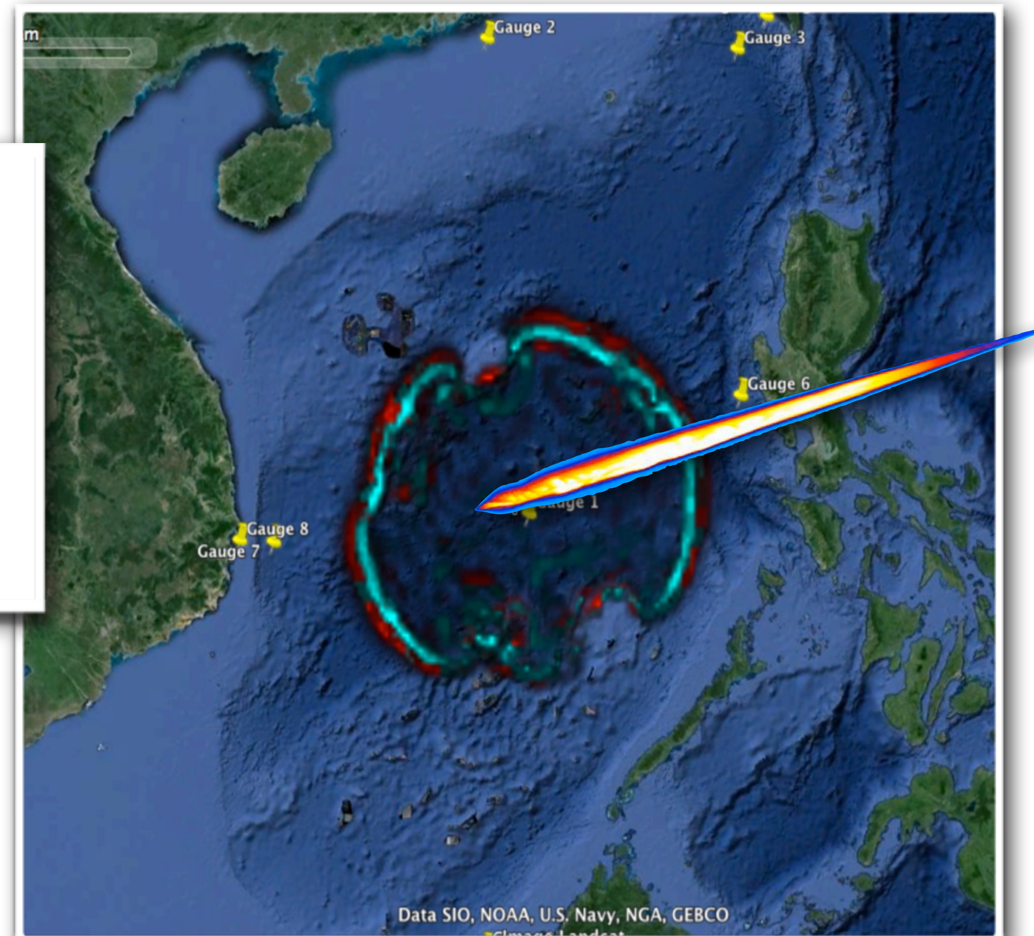
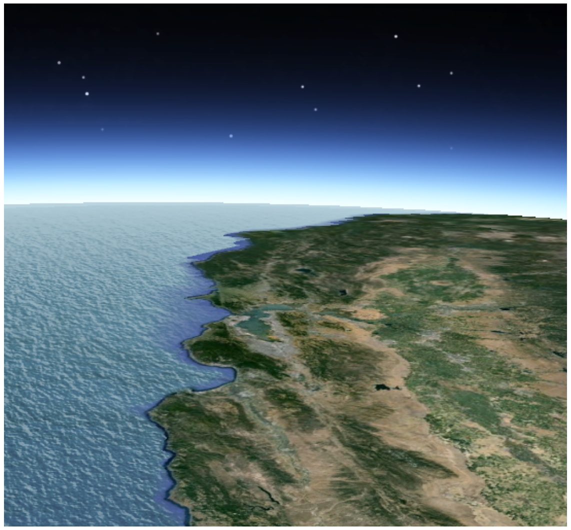
- Governing equations
- Atmosphere model
- Numerical Method
- Spherical charge V&V



Governing Equations

Inviscid perfect gas including body force due to gravity



- 3D Euler eqs. in strong conservation law form

$$\frac{d}{dt}\int_{\Omega} U\,dV + \oint_{\partial\Omega} (\mathbf{F}\cdot\hat{n})\,dS = \int_{\Omega} S\,dV$$

- The state vector of conserved variables is

$$U = (\rho, \rho u, \rho v, \rho w, \rho E)^T$$

- Flux density tensor and gravitational body force term are

$$\mathbf{F} = \begin{pmatrix} \rho u & \rho v & \rho w \\ \rho u^2 + p & \rho uv & \rho uw \\ \rho uv & \rho v^2 + p & \rho vw \\ \rho uw & \rho vw & \rho w^2 + p \\ u(\rho E + p) & v(\rho E + p) & w(\rho E + p) \end{pmatrix} \qquad S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -\rho g \\ -\rho w g \end{pmatrix}$$

Atmosphere Model

Hydrostatic Equilibrium

- For a stagnant fluid, gov. eqs. become a statement of hydrostatic equilibrium

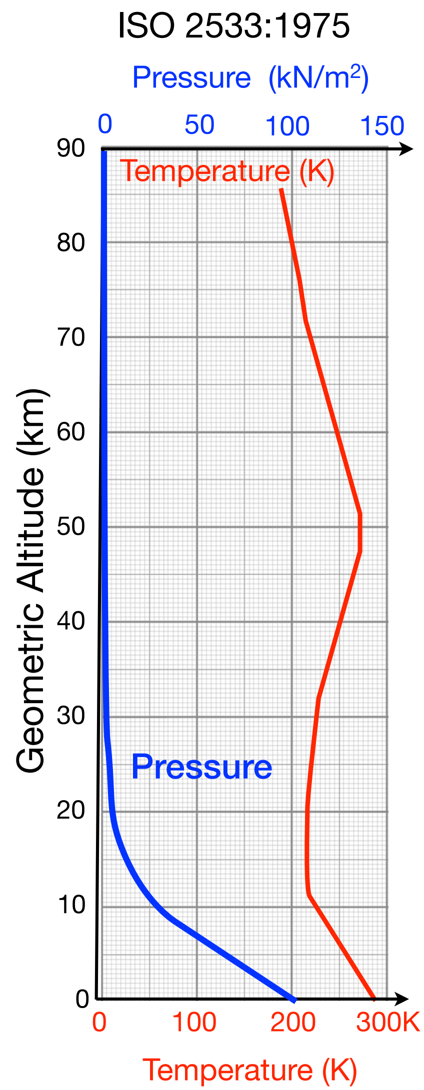
$$\frac{\partial p}{\partial z} = -\rho g_z$$

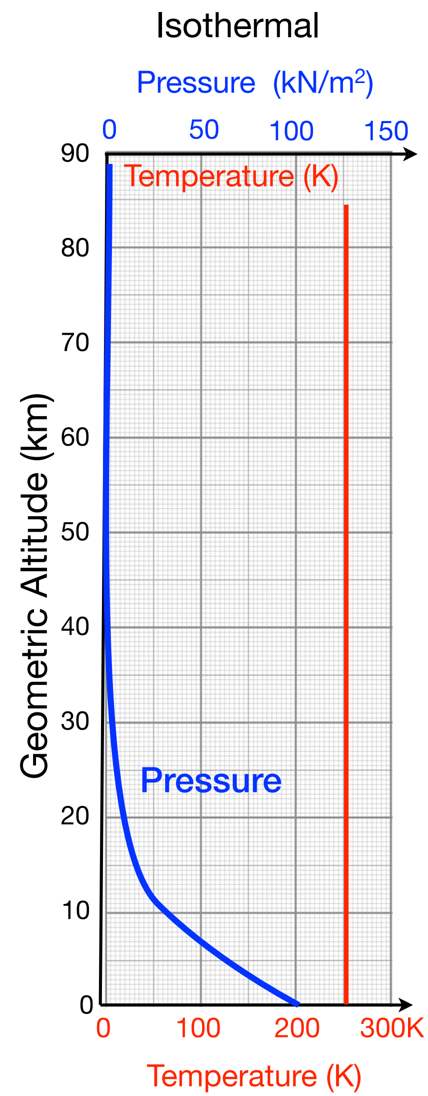
- Integrate for perfect gas under isothermal conditions gives a *scale height* model of atm.

$$\frac{p(z)}{p_\circ} = e^{-z/H}$$

- For real Earth earth atm. typically $H \approx 7 \rightarrow 8$ km

- Chose H to match pressure at both the airburst altitude and ground level.

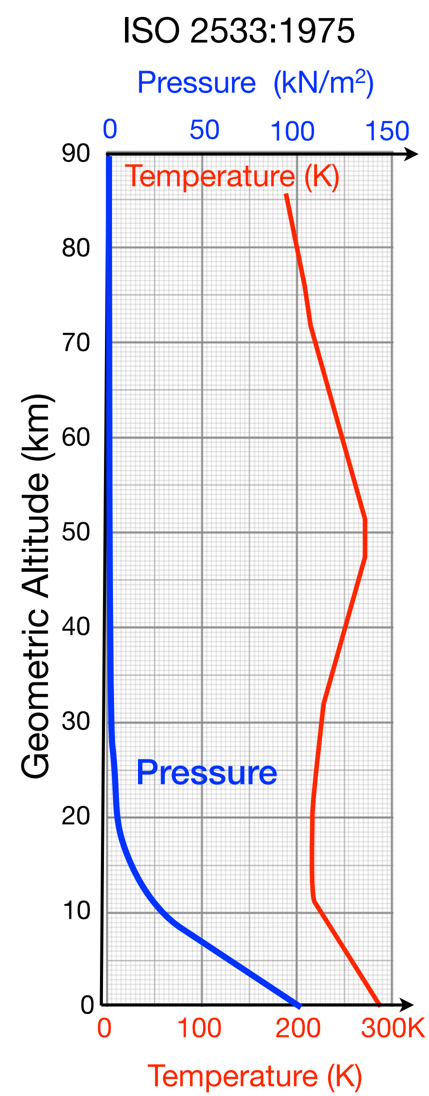


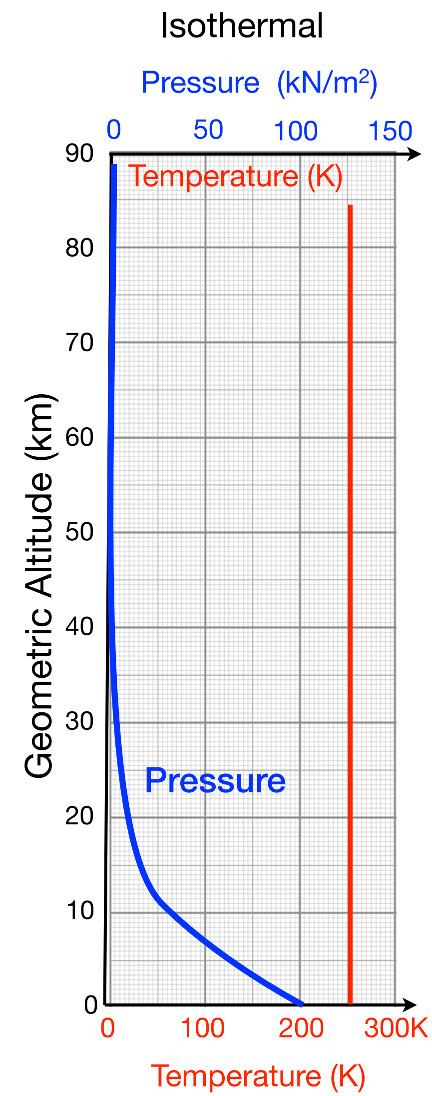


Atmosphere Model

1976 ISO Standard Atmosphere

- Use Atmosphere model based on 1976 Standard Atmosphere (ISO 2533:1975)
- Chose the scale height, H, to match pressure at both the airburst altitude and ground level.
- Gives correct blast strength at altitude and correct overpressure at ground





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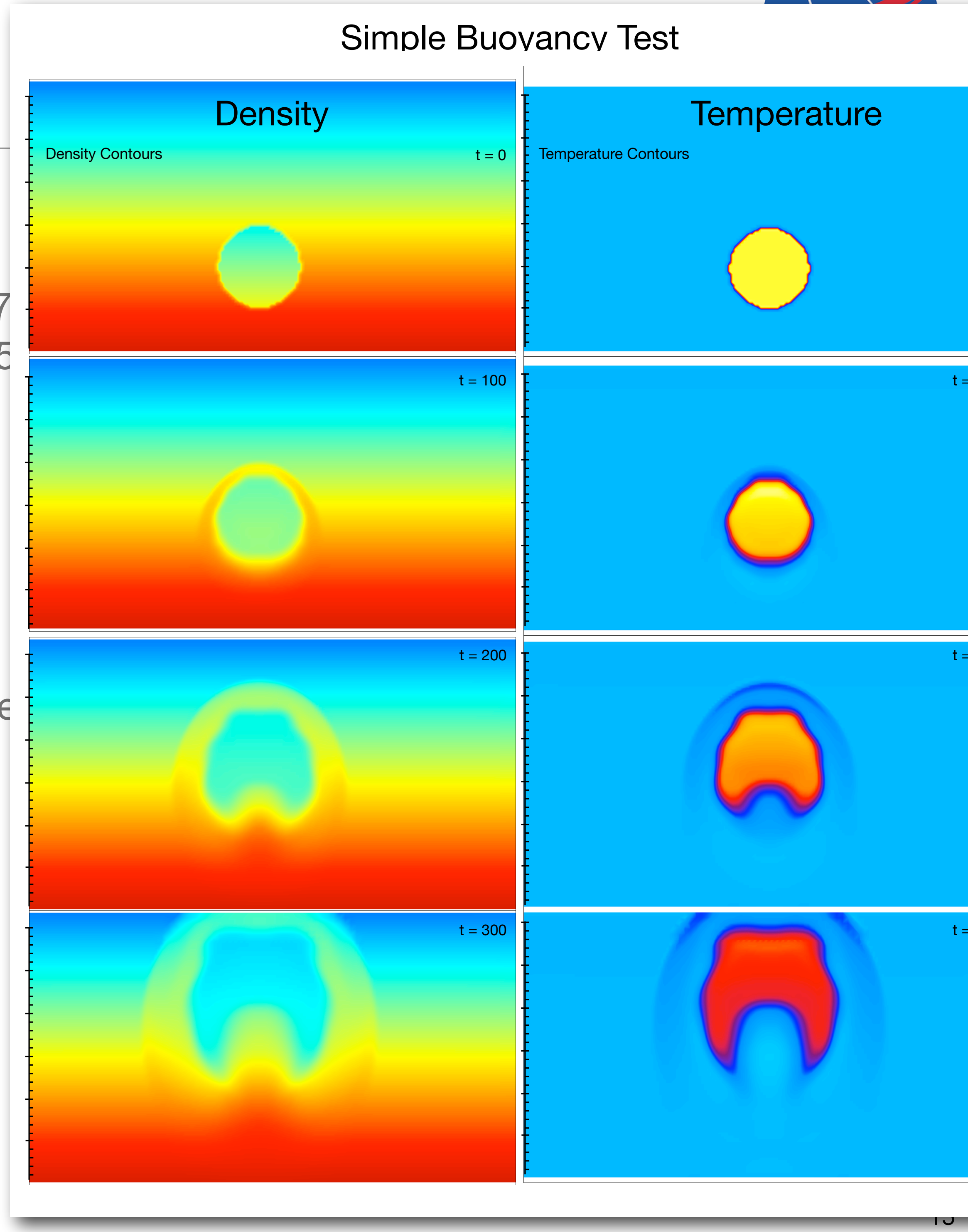
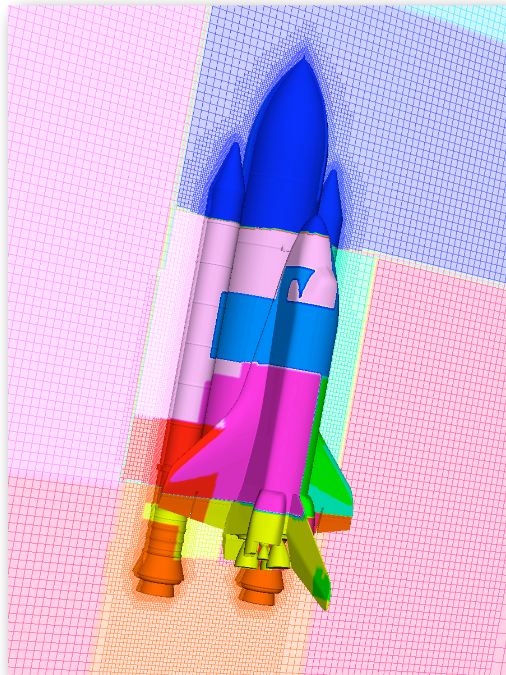
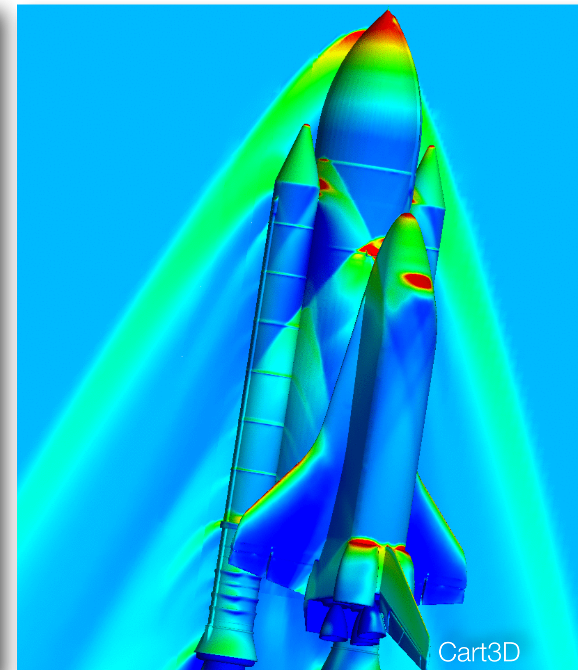


Solver: Cart3D Overview

Production solver based on cut-cell Cartesian mesh method

- Fully-automated mesh generation for complex geometry
- Unstructured Cartesian cells
- Fully-conservative finite-volume method
- Multigrid accelerated 2nd-order upwind scheme
- Dual-time approach for unsteady flow
- Excellent scalability through domain decomposition
- Broad use throughout NASA, US Government and industry
  - Over 500 users in aerospace community
  - One of NASAs most heavily used production solvers, large validation database





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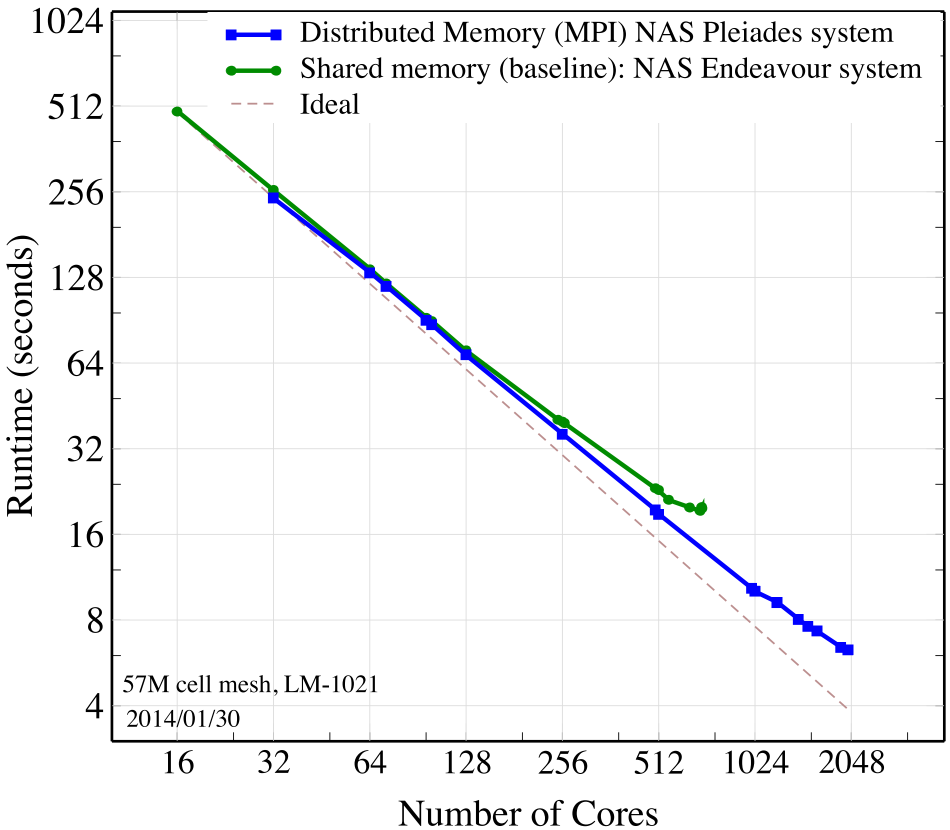
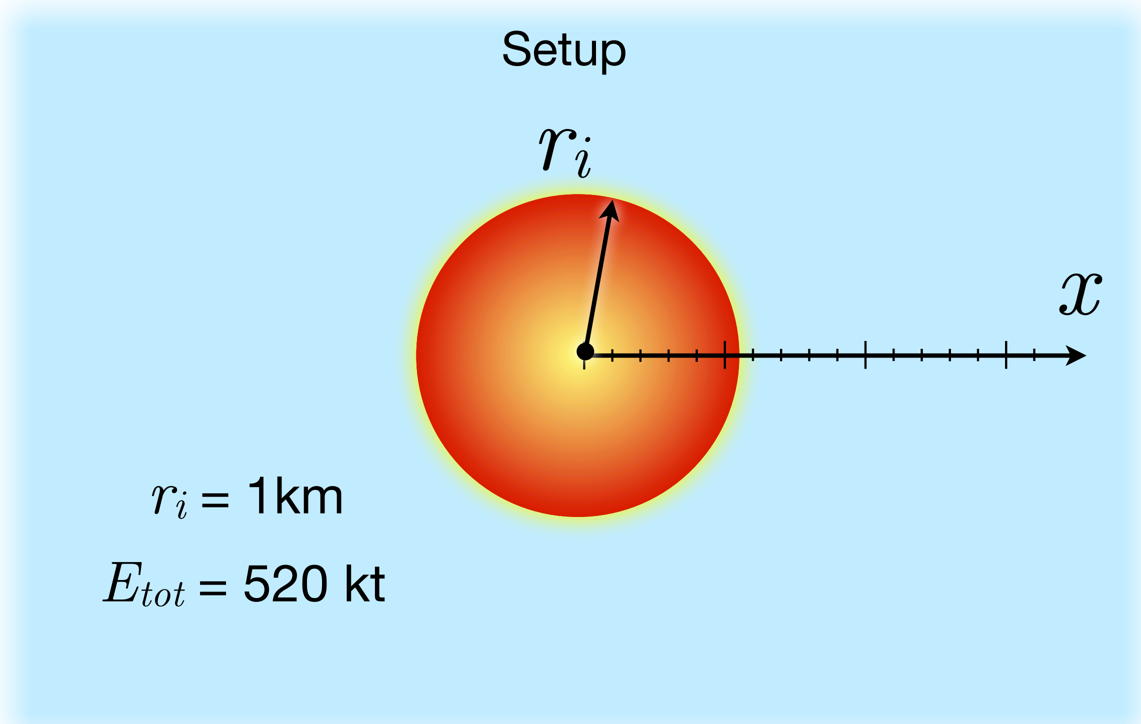


Basic Verification & Validation

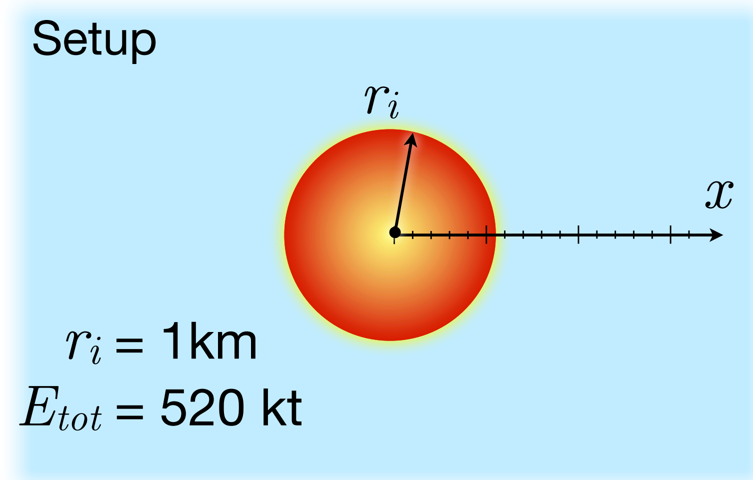
Blast from a spherical charge

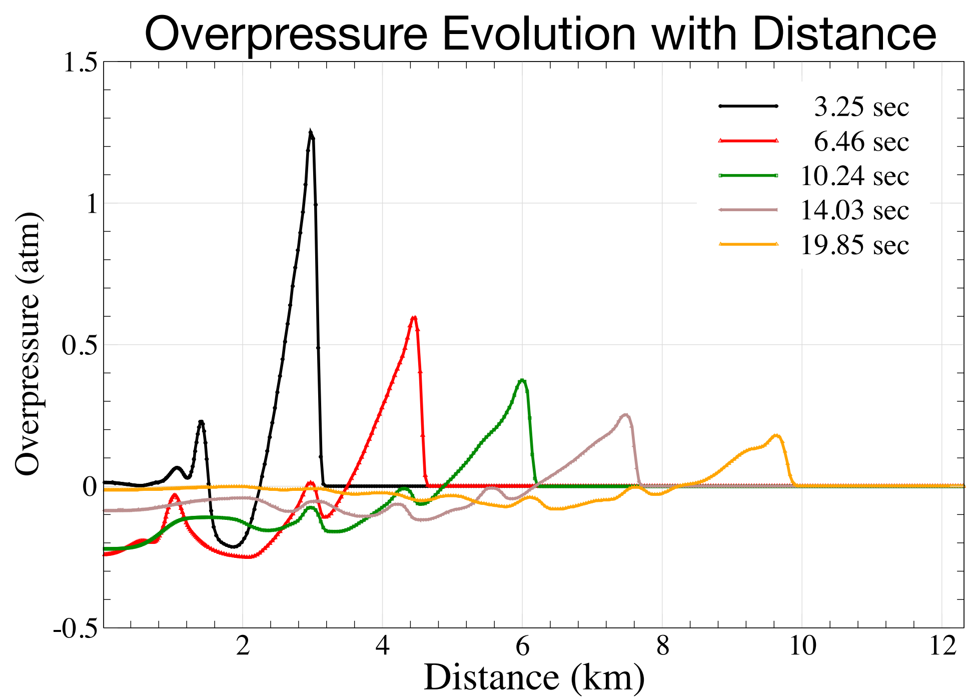


Basic Verification & Validation

Blast from a spherical charge

- Static spherical charge with
  - No buoyancy
  - E_{tot} = 520 kt of TNT
  - Initial radius, r_i = 1km
- Classical refs.
  - Brode, H. L.,Blast wave from a spherical charge, *Phys. Fluids* (1959)
  - D. L. Jones. Intermediate strength blast wave. *Phys. Fluids* (1968)



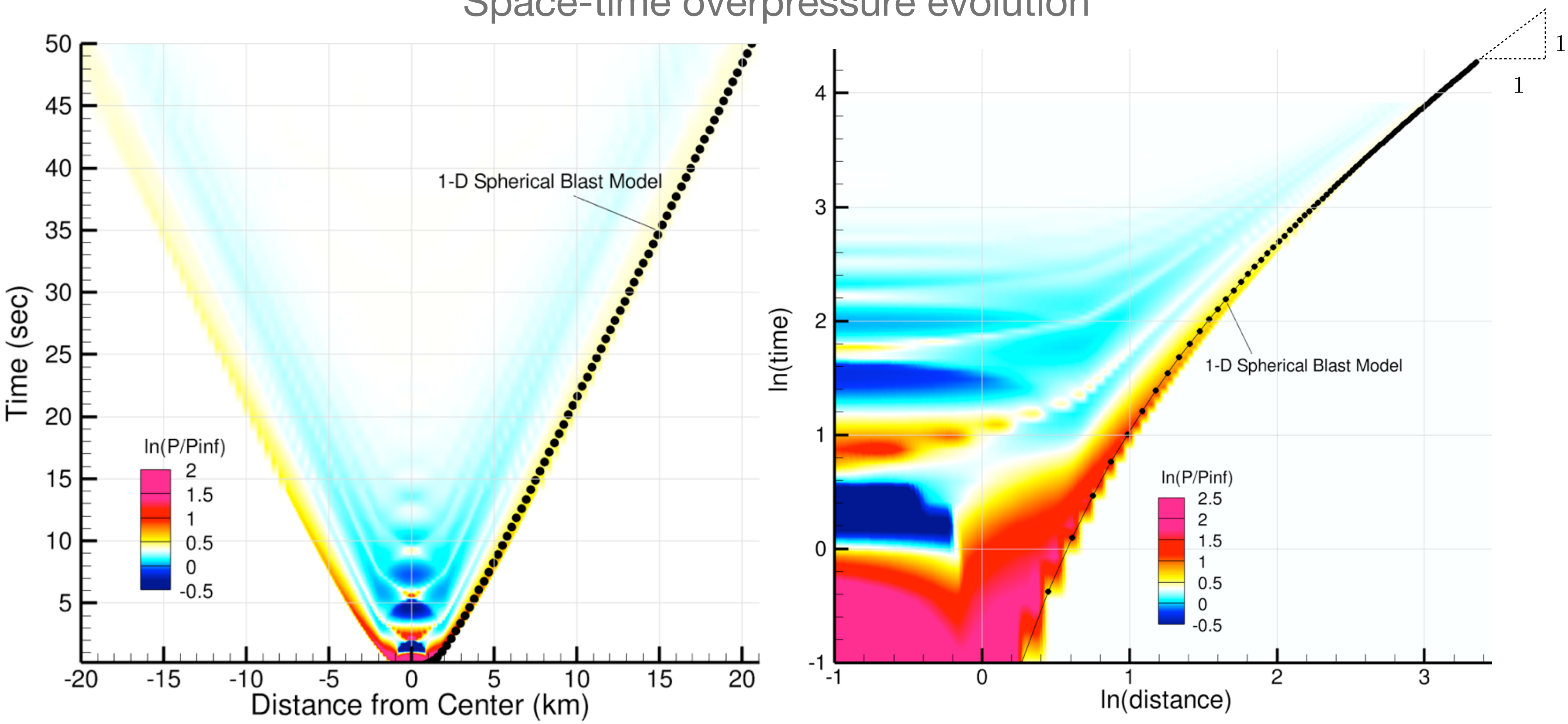


Basic Verification & Validation

Blast from a spherical charge

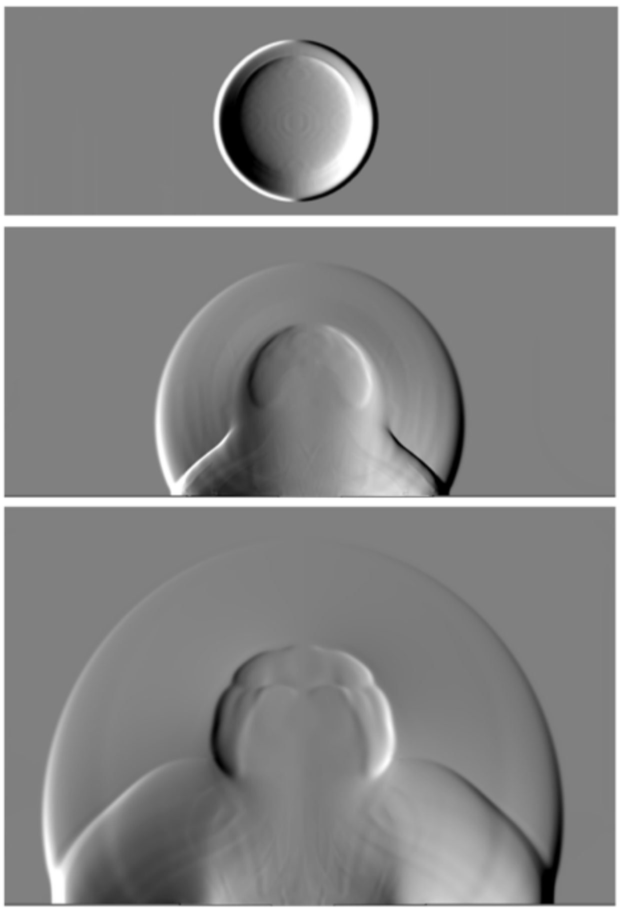
- E_{tot} = 520 kt, Initial radius, r_i = 1km, no buoyancy
- Compare with 1-D spherical blast code

Space-time overpressure evolution



Basic Verification & Validation

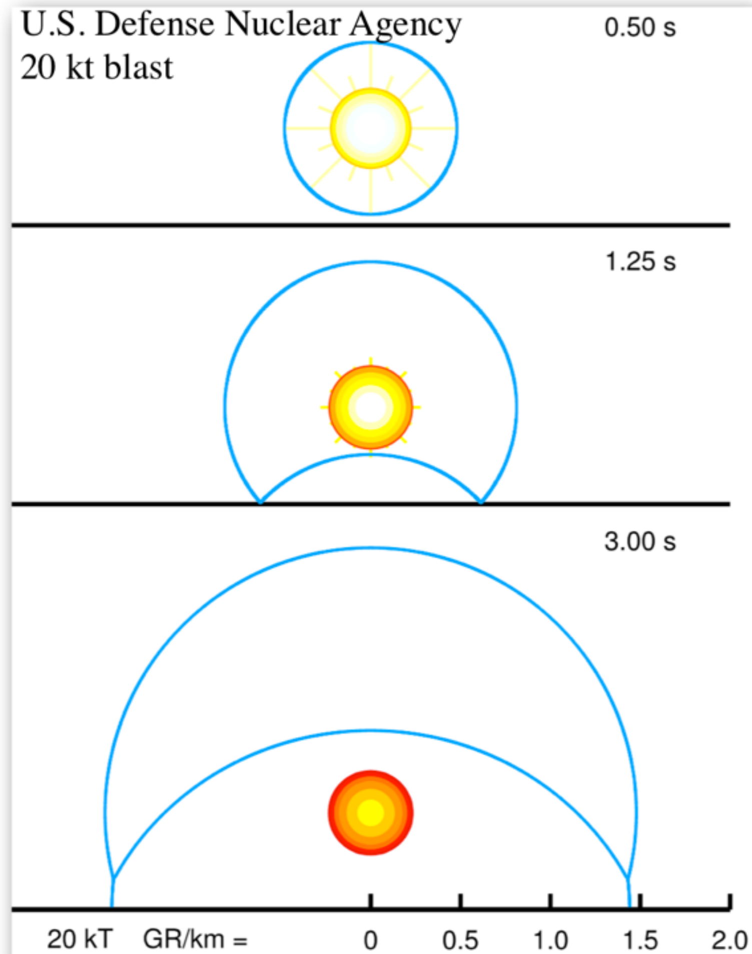
Blasts over ground plane



Spherical airburst

Simple shock reflection

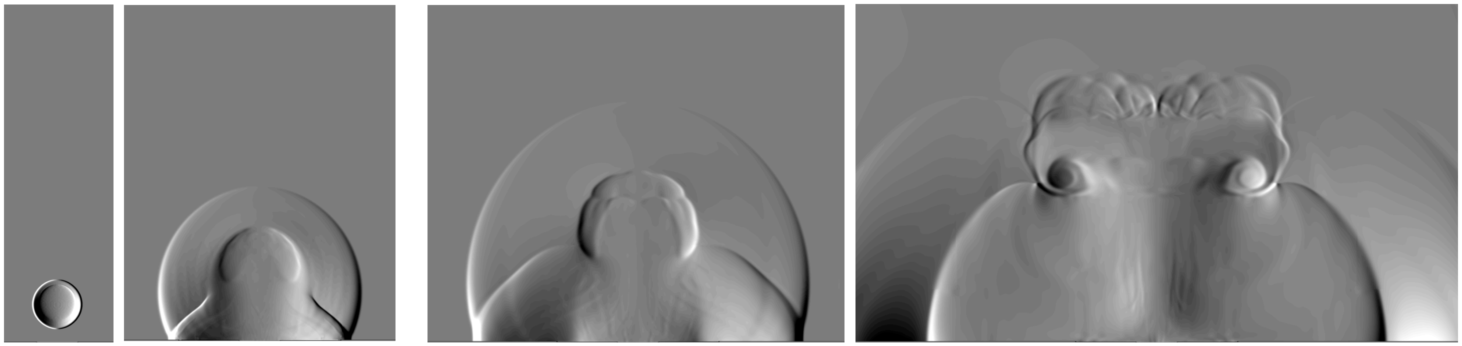
Mach stem formation



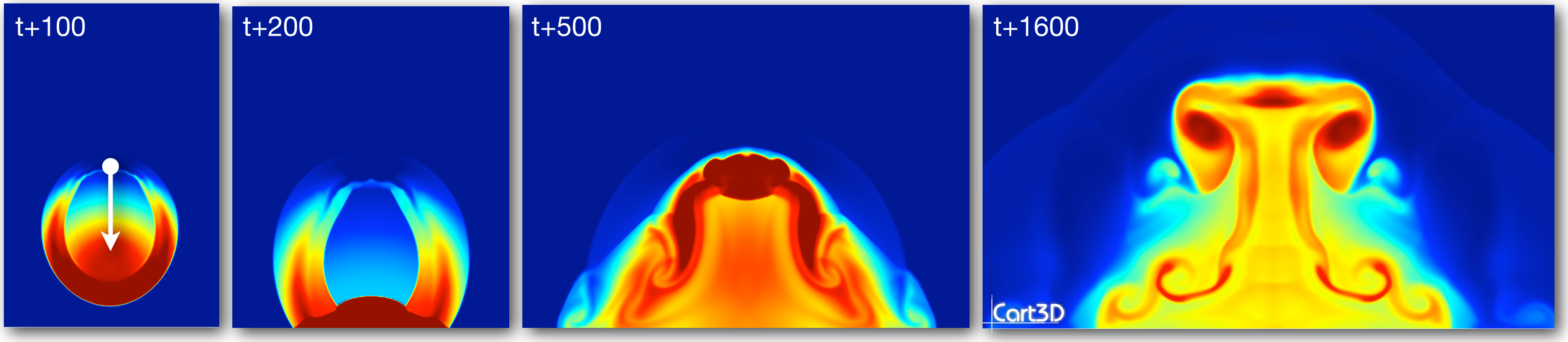
Basic Verification & Validation

Blasts over ground plane

- Numerous examples static and moving blasts over ground plane with buoyancy
  - Static airburst with buoyancy



  - Moving airburst



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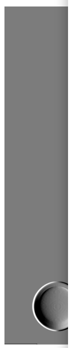

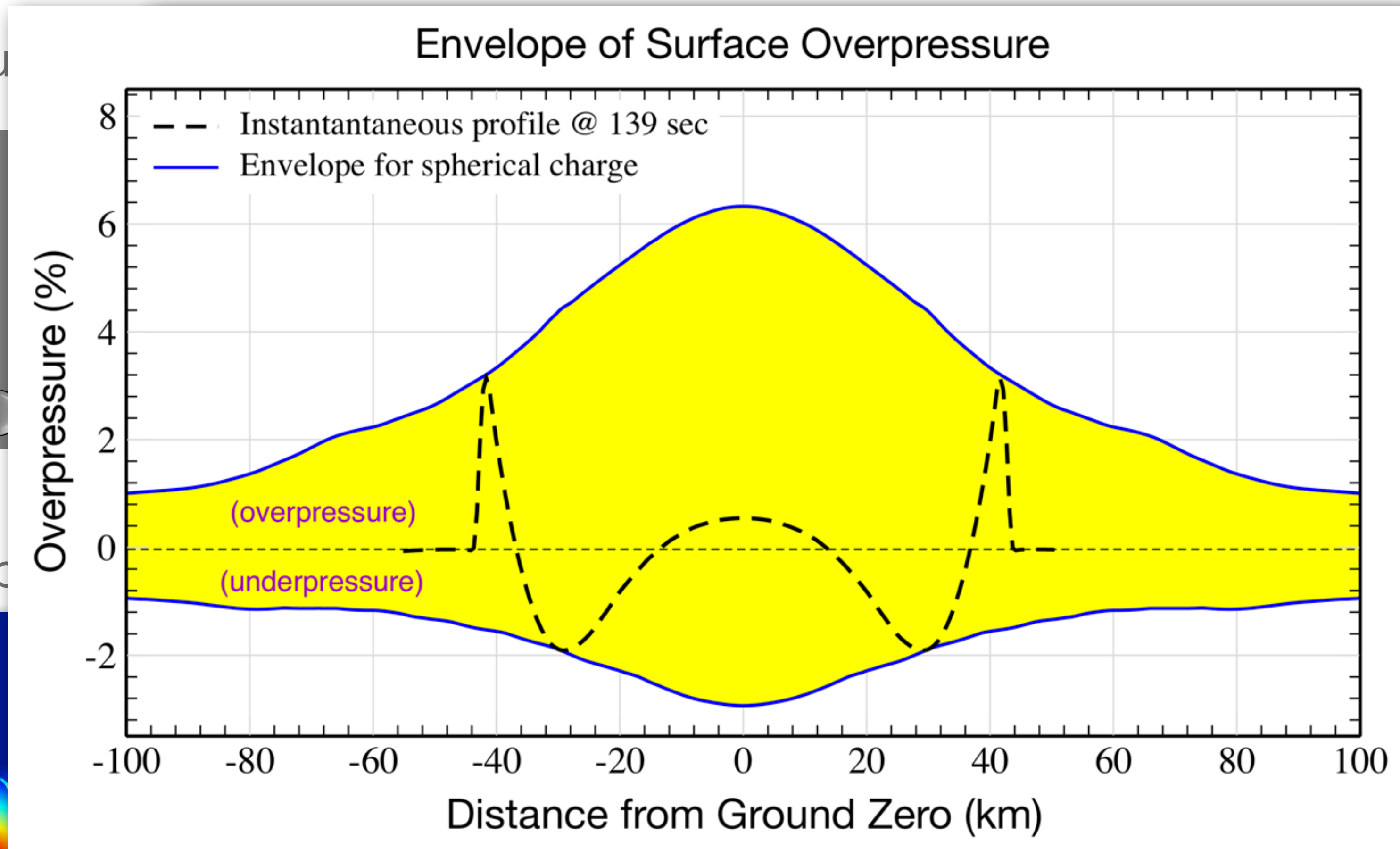

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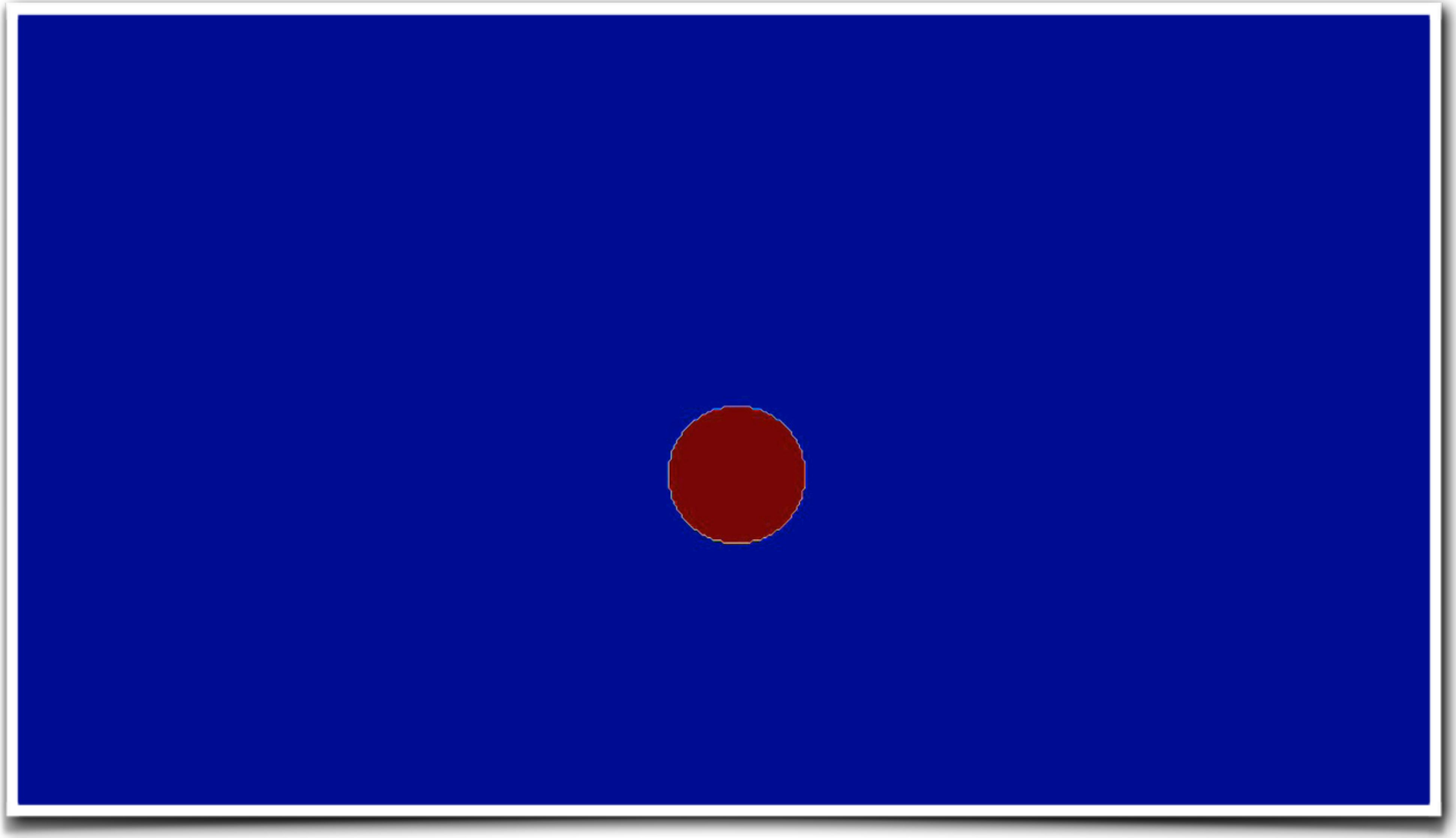

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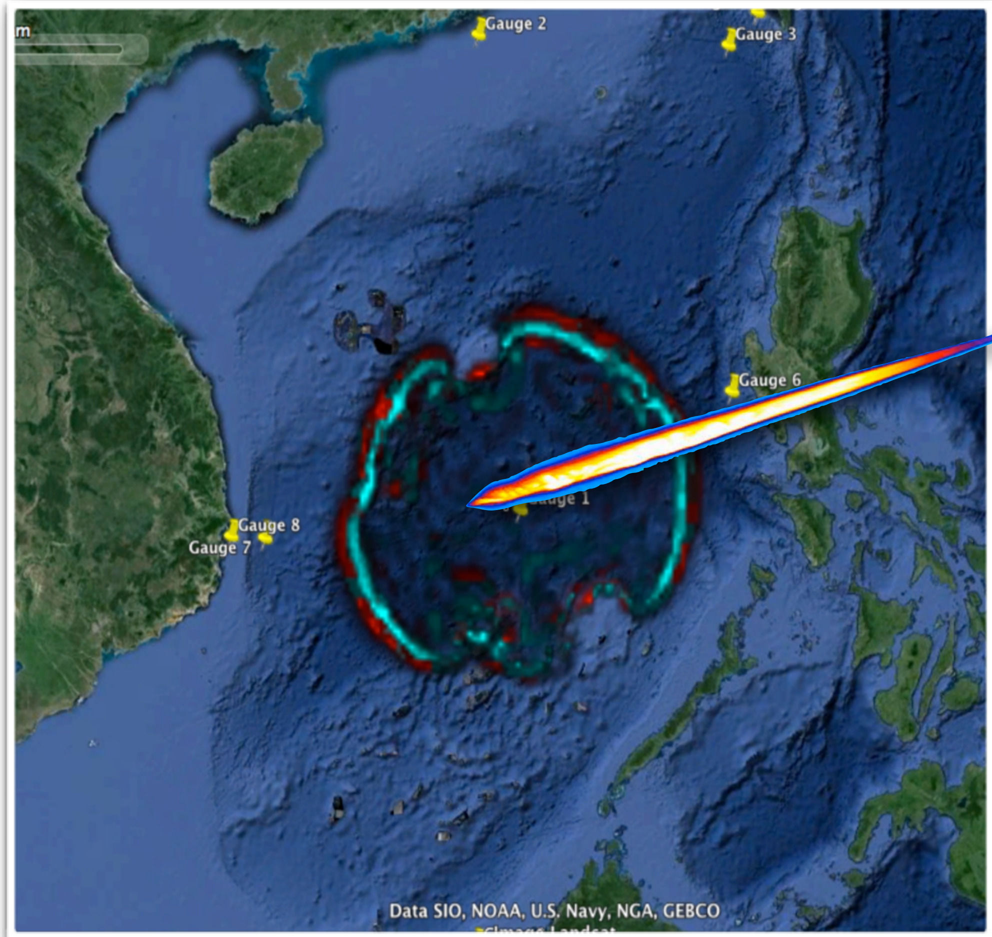
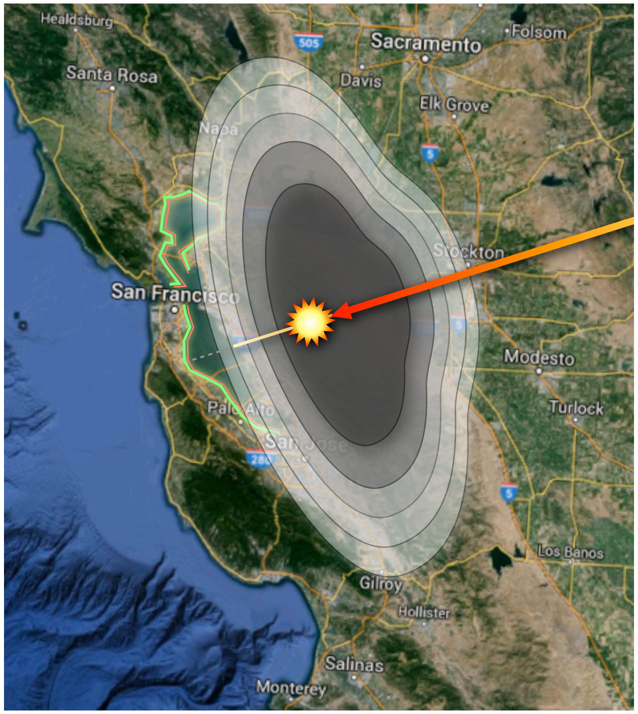


Deposition of Mass, Momentum & Energy

Goal is accurate prediction of surface effects from energy deposition inputs

- Focus on ground footprint, not near-field physics
- Abstract entry physics as simply sources of mass, momentum & energy
- Entry characterized by *energy deposition profile* via:
  - Models (e.g. ReVelle, Ceplecha, H&G, Shuvalov)
  - Simulations (Task 2, CTH, ALE3D, Shuvalov, Boslough)
  - Light-curve derived profiles (Jenniskins, Popova)
  - Infrasound based energy deposition (Brown, ReVelle)



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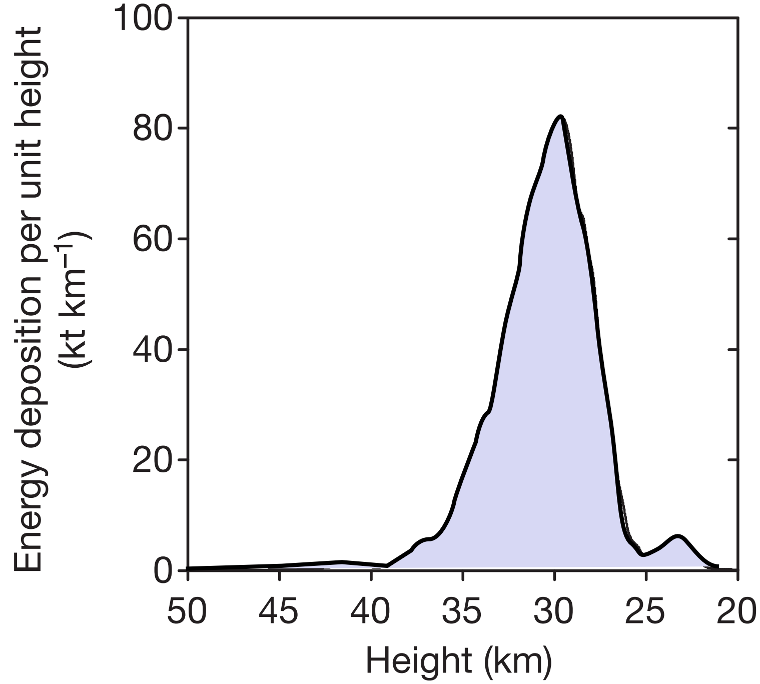
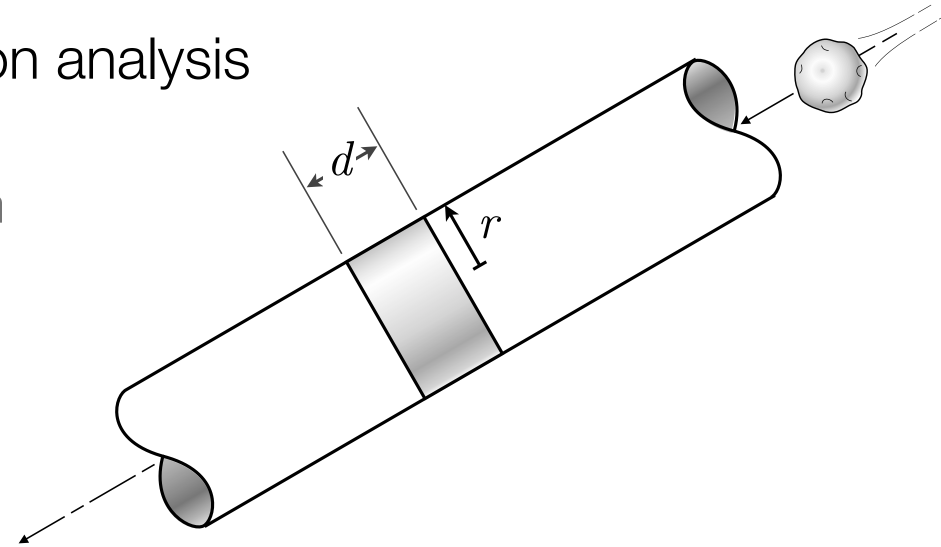
Need to derive source terms from deposition profiles



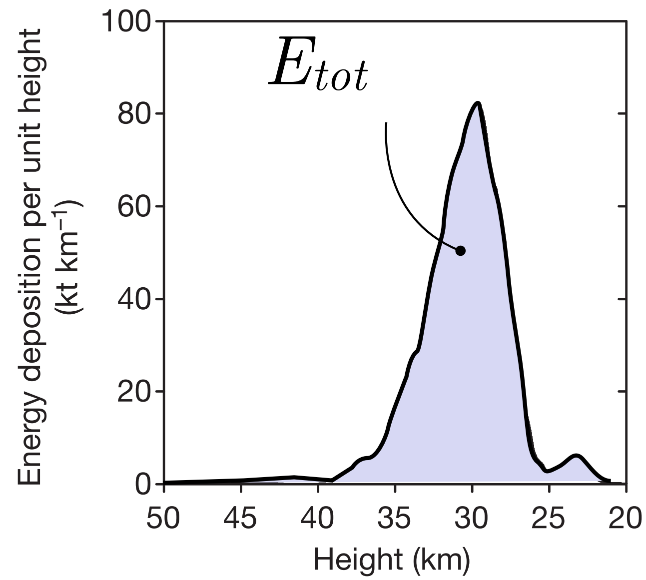
Deposition of Mass, Momentum & Energy

Derive source terms through conservation analysis

- Release energy, mass and momentum into a corridor of known radius, r
- Over each time step, Δt, the meteor travels a distance $d = V\Delta t$
  - Given energy deposition profile as a function of altitude
  - Derive time-dependent sources for mass, momentum and energy



Brown *et al.*, Nature, November 2013

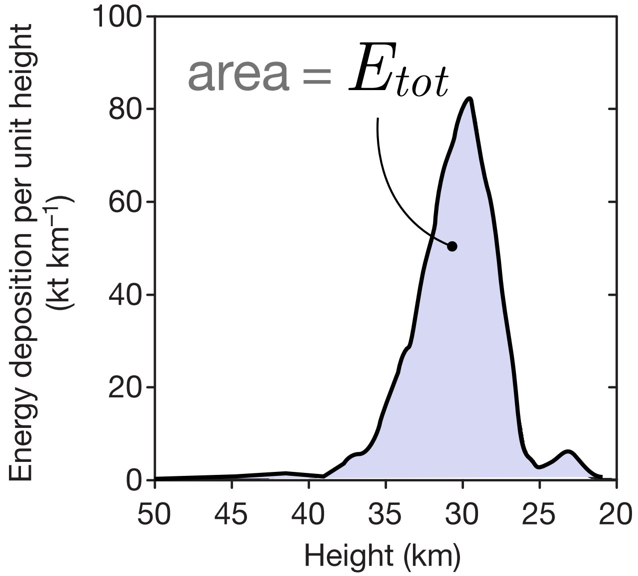


Deposition of Mass, Momentum & Energy

Conservation of energy

- Given energy deposition we know the total energy released is area under profile

$$E_{tot} = \int \frac{dE}{dh}\, dh$$



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- For known entry angle, can rescale profile to be energy released along trajectory, x

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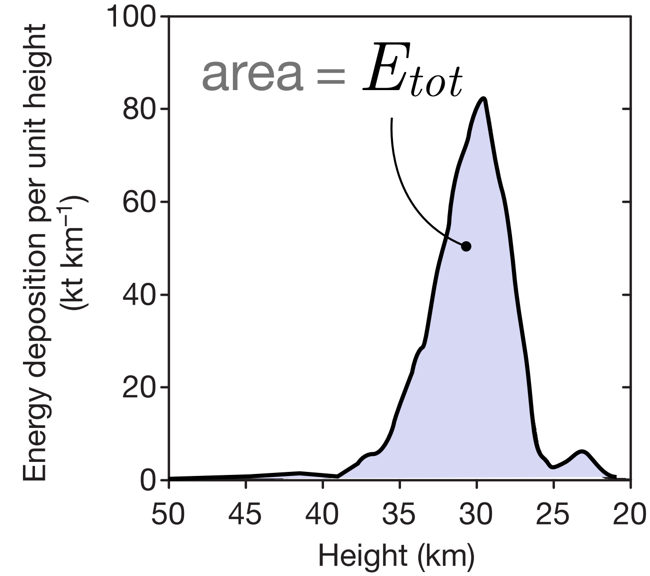

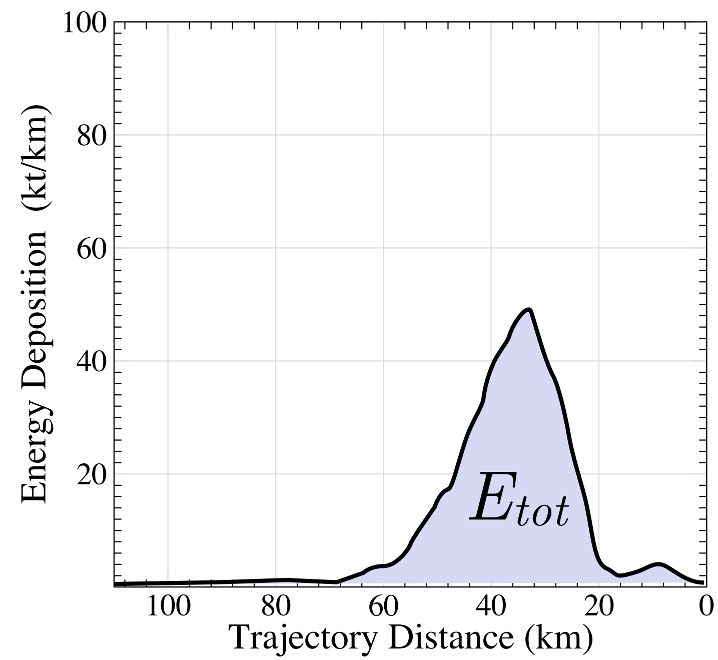

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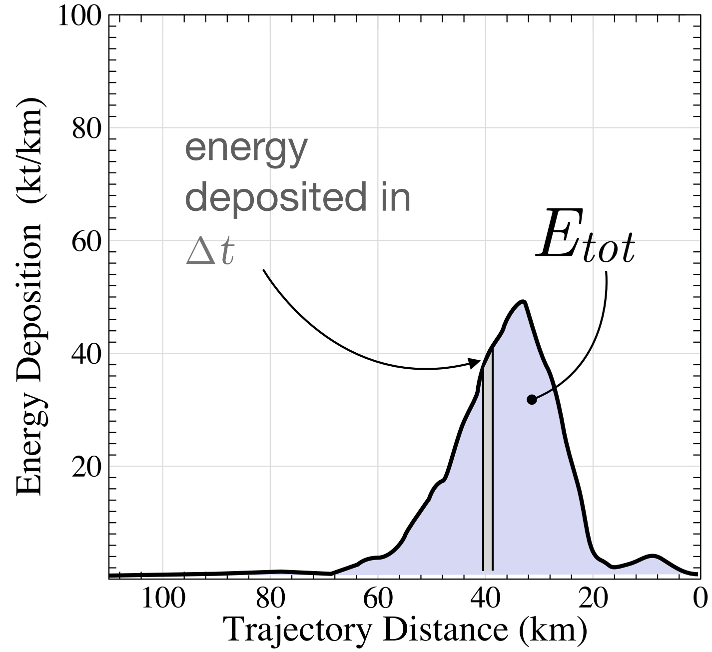
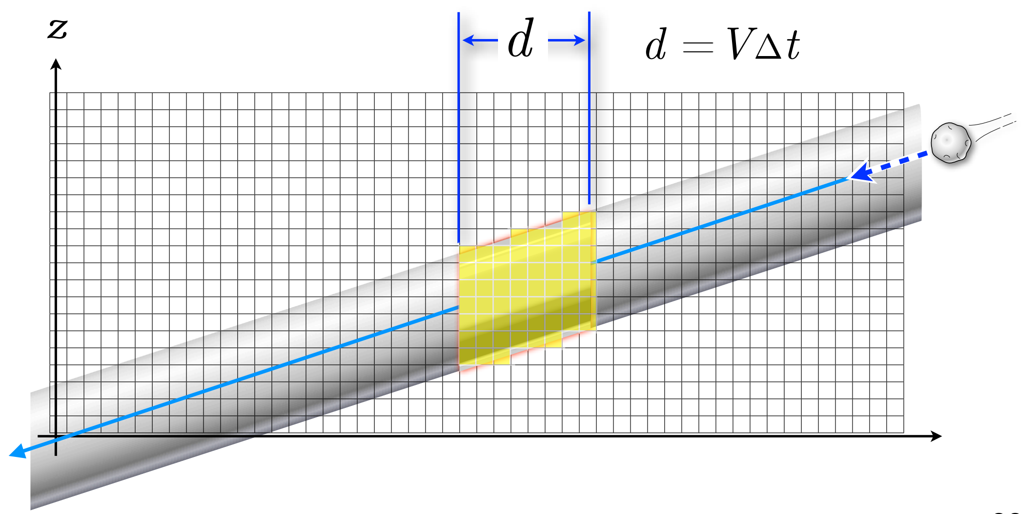


- For known entry angle, can rescale profile to be energy released along trajectory, x

$$E_{tot} = \int \frac{dE}{dx}\, dx$$

- This energy gets released into the mesh cells which intersect the tube surrounding the meteor at each time step, Δt



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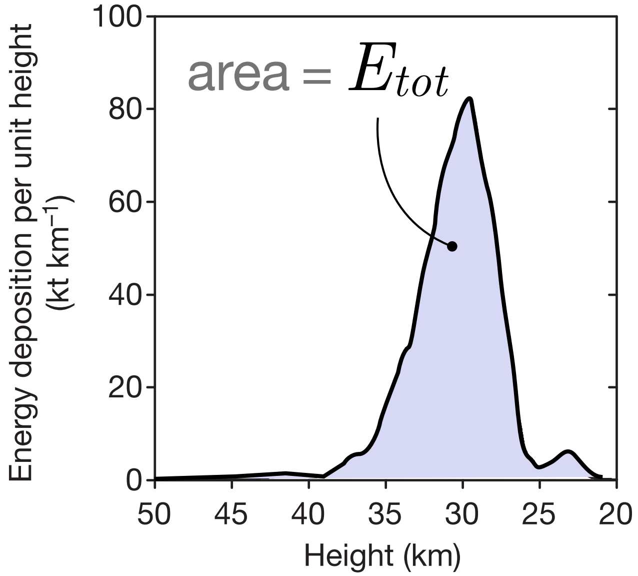

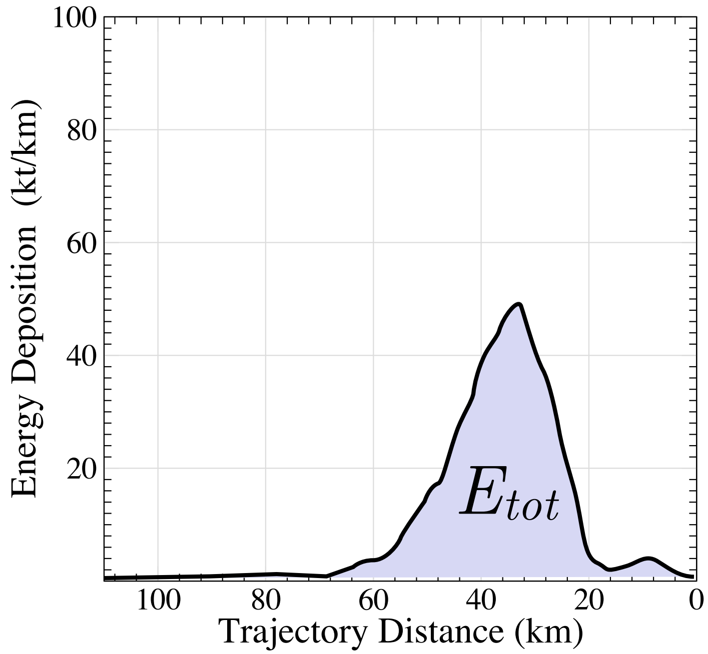

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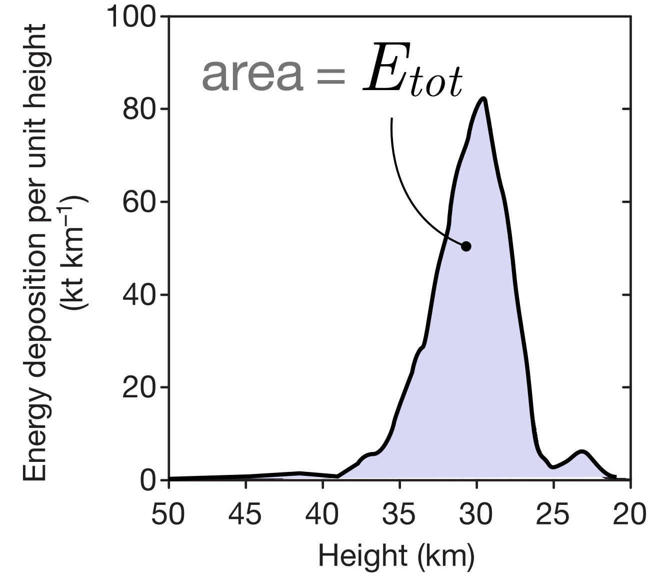
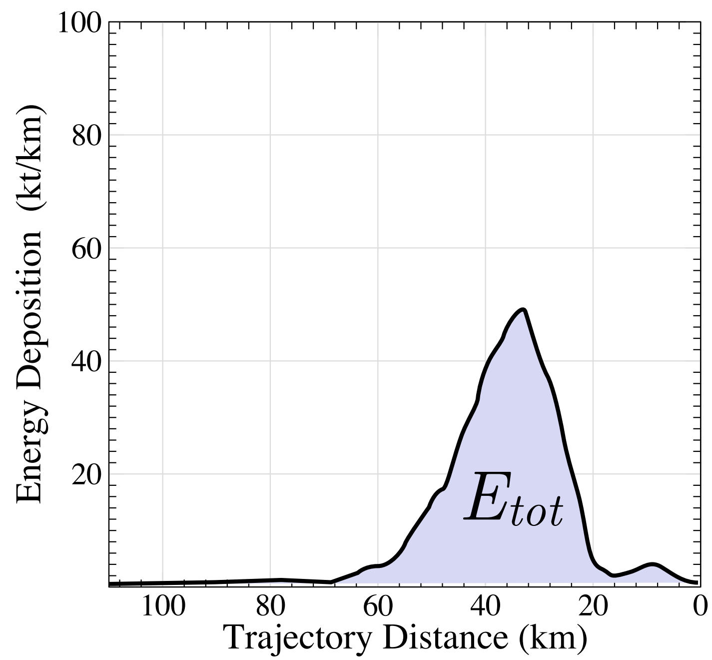
Alternatively, E_{tot} is the work done by the atmosphere to arrest the meteor





Deposition of Mass, Momentum & Energy

Conservation of energy

- Given energy deposition we know the total energy released is area under profile

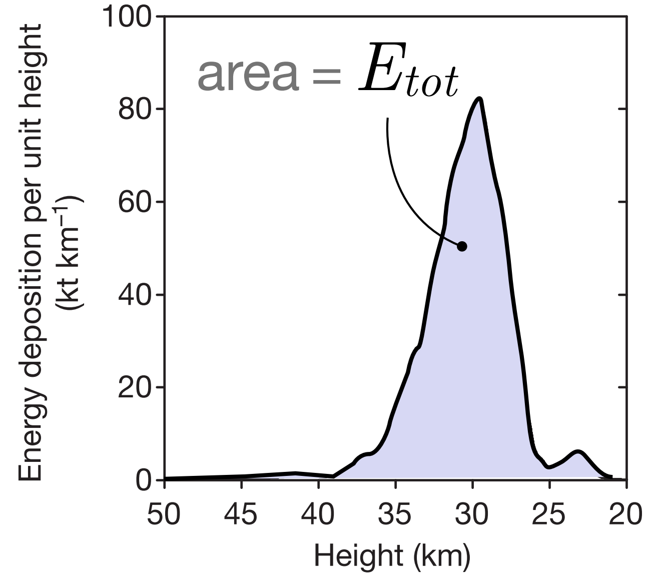
$$E_{tot} = \int \frac{dE}{dh}\, dh$$

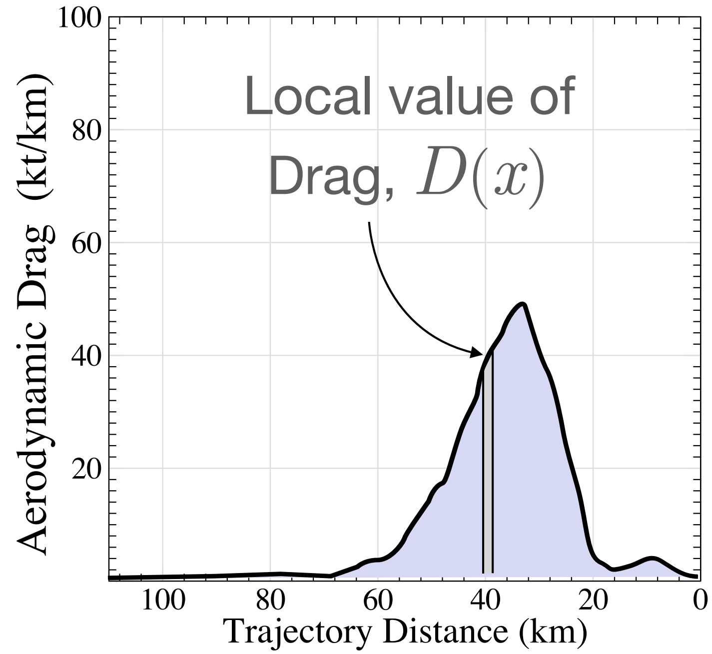
- For known entry angle, can rescale profile to be energy released along trajectory, x

$$E_{tot} = \int \frac{dE}{dx}\, dx$$

- Since work = (force x distance), and aerodynamic drag is doing all the work, this profile **is identically drag** along the trajectory

$$E_{tot} = \int \frac{dE}{dx}\, dx = \int D(x)\, dx$$



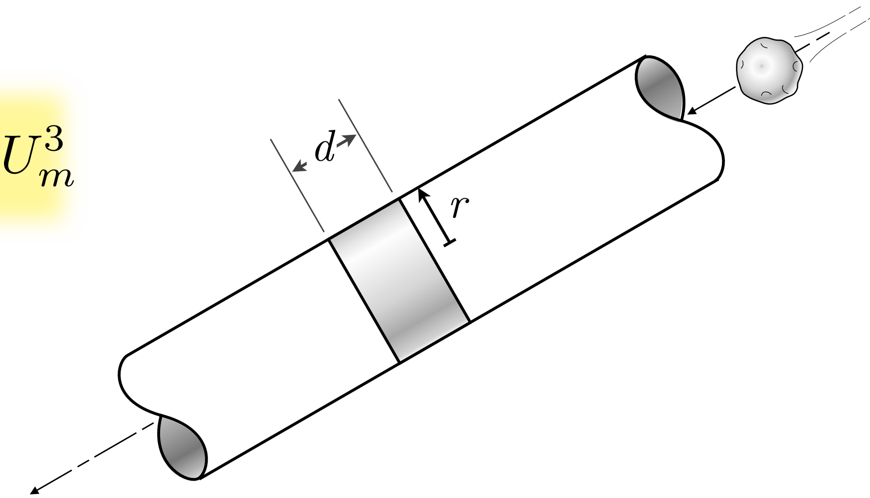


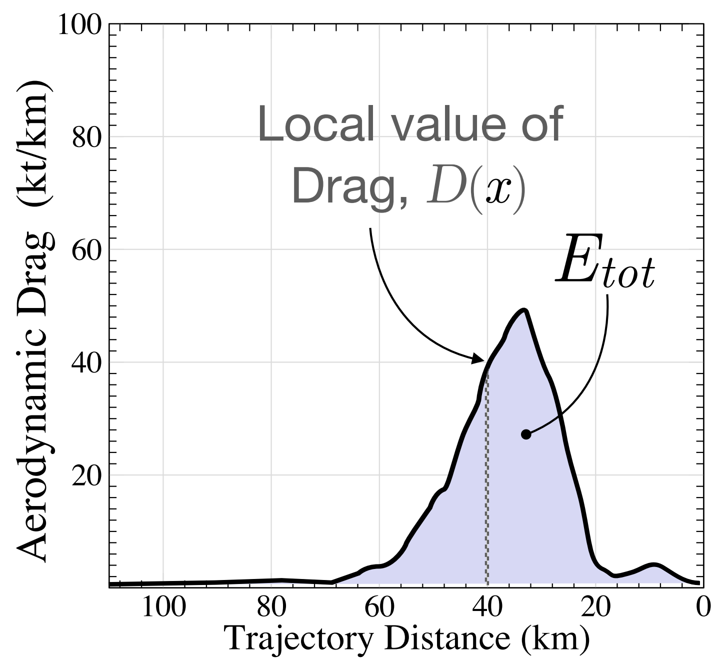
Deposition of Mass, Momentum & Energy

Conservation of mass & momentum

- Mass loss equation

$$\frac{dM}{dt} = -\sigma C_D S_m \frac{1}{2} \rho_{\text{air}} U_m^3$$





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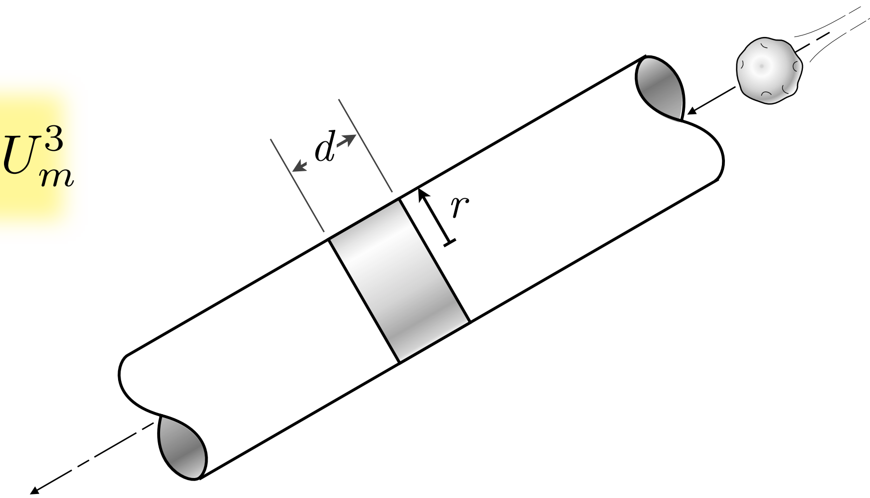
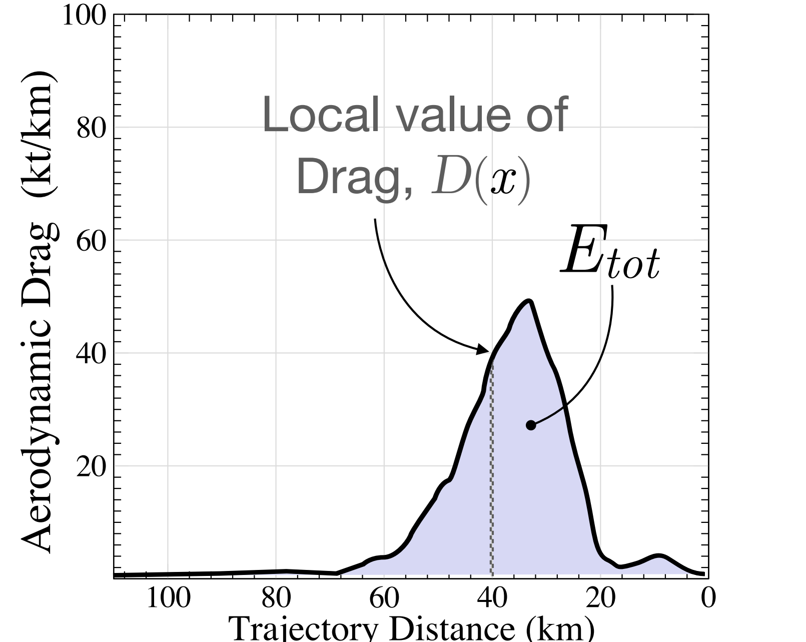


- Since aerodynamic drag is

$$D = C_D S_m q_\infty \quad \text{with} \quad q_\infty = \frac{1}{2}\rho_{\mathrm{air}} U_m^2$$

- So, rate of mass loss is

$$\frac{dM}{dt} = -\sigma D U_m$$



Deposition of Mass, Momentum & Energy

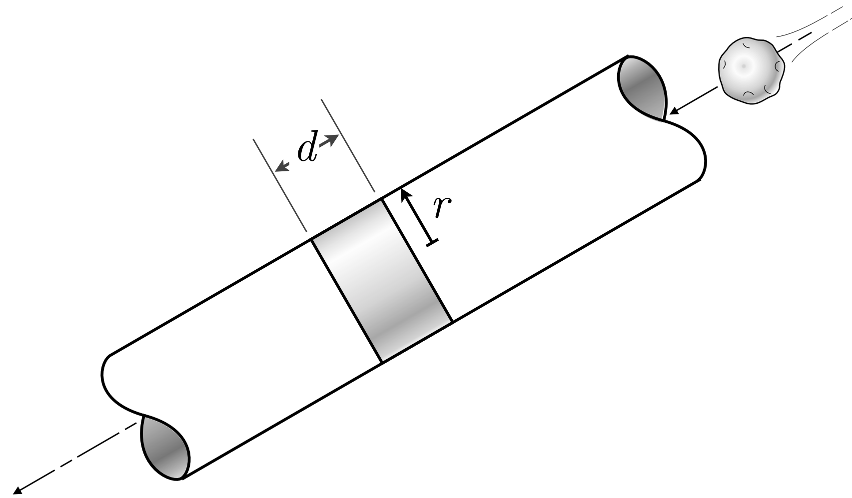
Conservation of mass & momentum

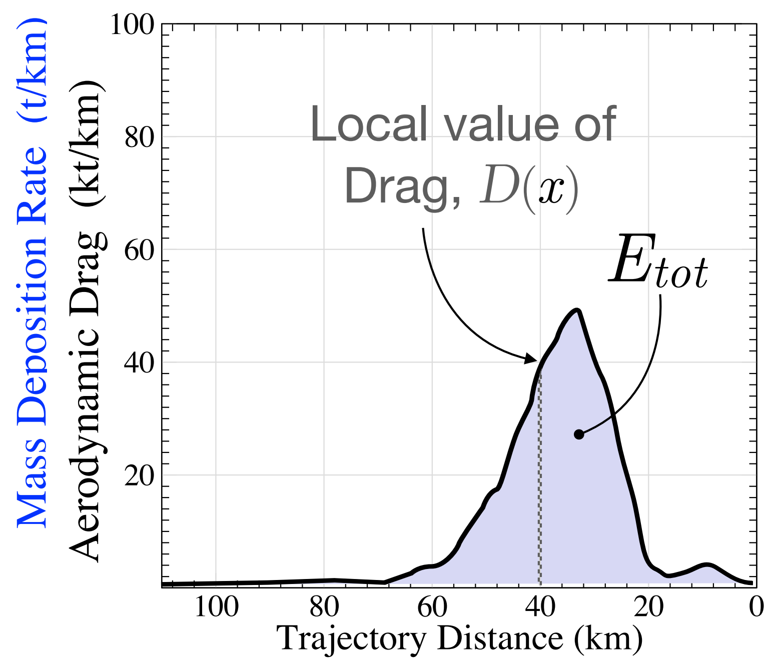
- So, rate of mass loss is $\dfrac{dM}{dt} = -\sigma D U_m$

- Since $\dfrac{dM}{dt} = \dfrac{dM}{dx}\dfrac{dx}{dt} = \dfrac{dM}{dx}U_m$

- We can relate the mass deposited along the trajectory directly to drag.

$$M_{tot} = \int \frac{dM}{dx}dx = -\int \sigma D(x)dx$$





Deposition of Mass, Momentum & Energy

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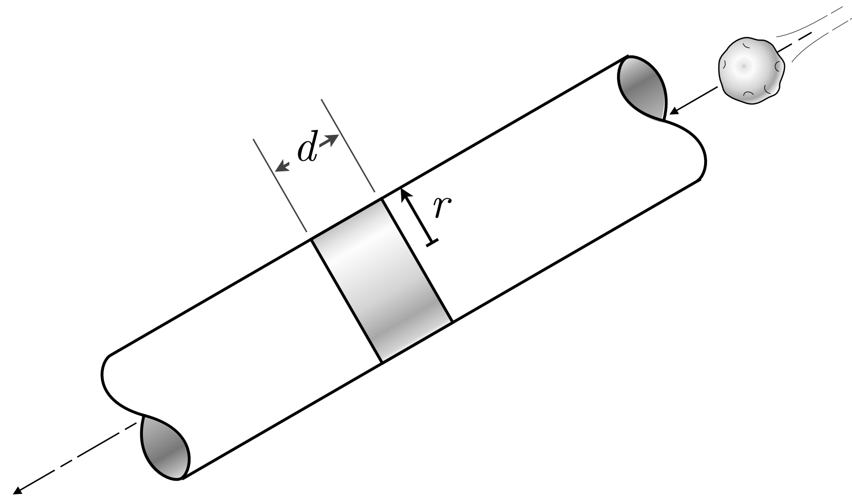

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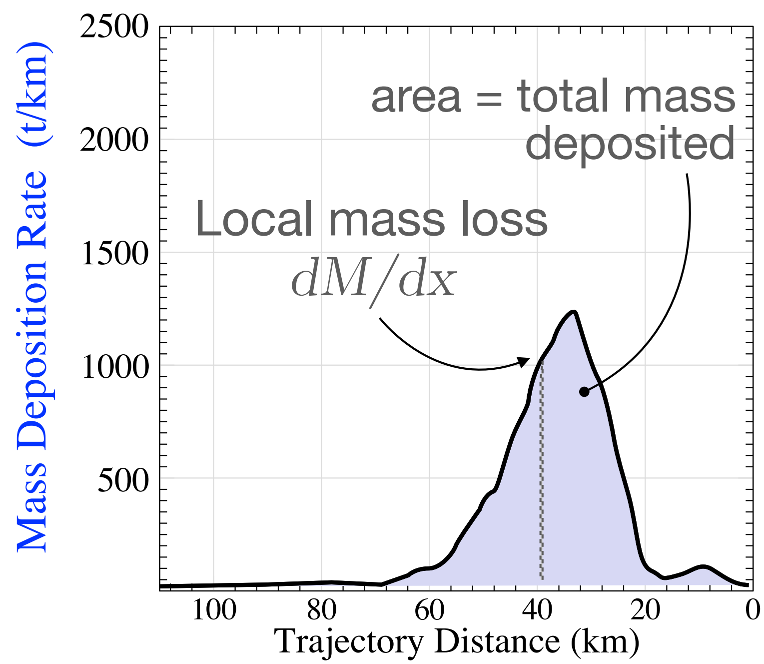
$$M_{tot} = \int \frac{dM}{dx}dx = -\int \sigma D(x)dx$$

- Area under profile is now the total mass deposited $M_{\text{tot}} = (M_{\text{entry}} - M_{\text{GroundFragments}})$

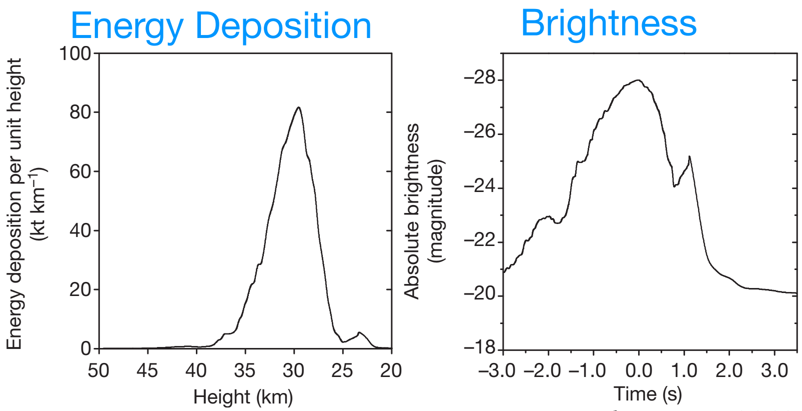
- From mass deposition and velocity, we also know momentum deposition



Validation: Chelyabinsk Meteor

February 15, 2013

- 12,500 metric tons, 19.8 m diameter
- Trajectory:
  - 18.6 km/sec, (~Mach 61.7)
  - 18° entry angle
- Data
  - Ground Damage (glass breakage data)
  - Shock arrival times
  - Light curve reconstruction
  - Energy deposition from light curve & infrasound



Brown et.al, Nature, 2013

Very well studied event, simulations of virtually all aspects of entry, breakup, analysis of composition, blast propagation, ground damage, etc.

Validation: Chelyabinsk Meteor

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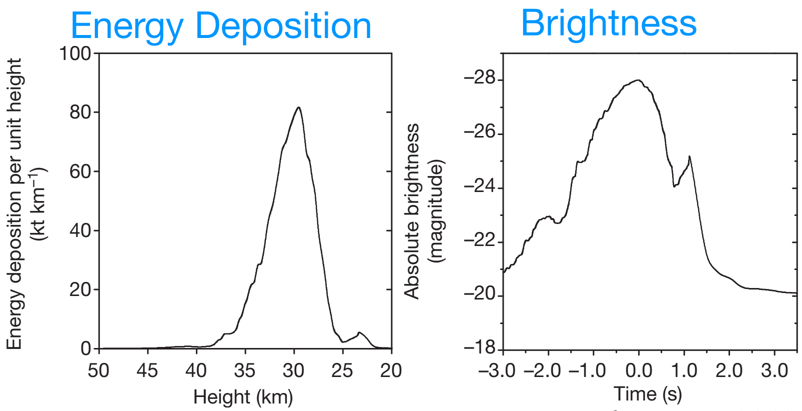


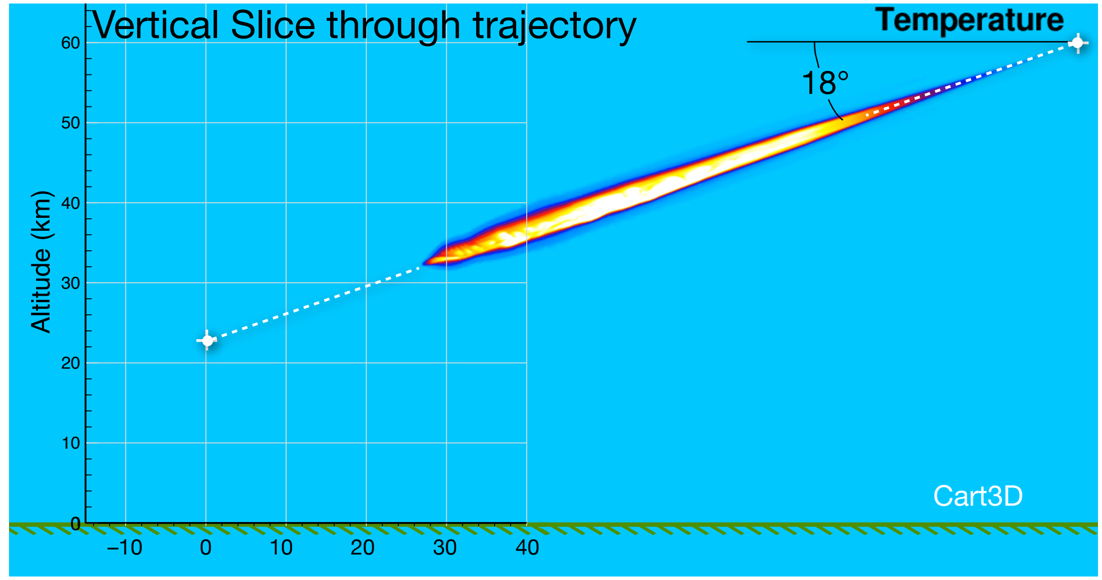
Brown et.al, Nature, 2013

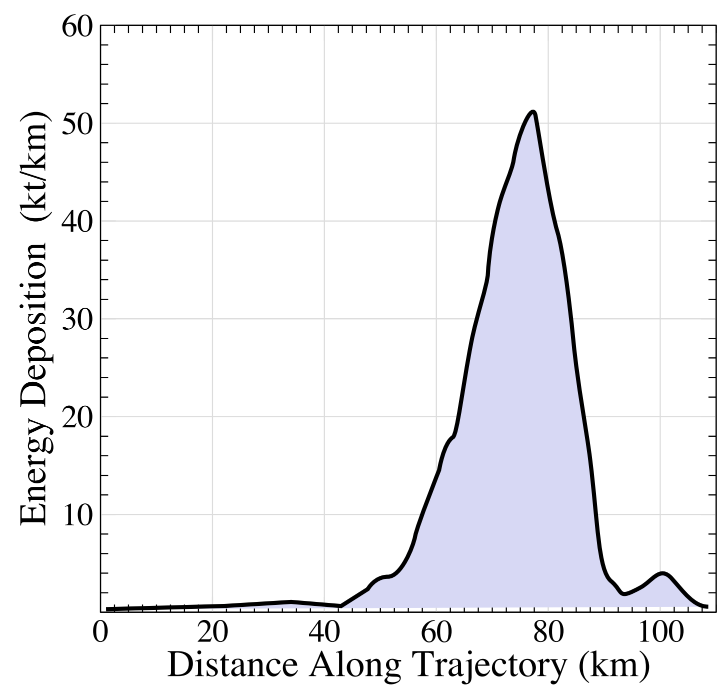
- Primary references used
  - Popova & Jenniskens *et al*., Science Express, November 2013
  - Brown *et al*., Nature, November 2013
  - Chelyabinsk Airburst Consortium, + various other media

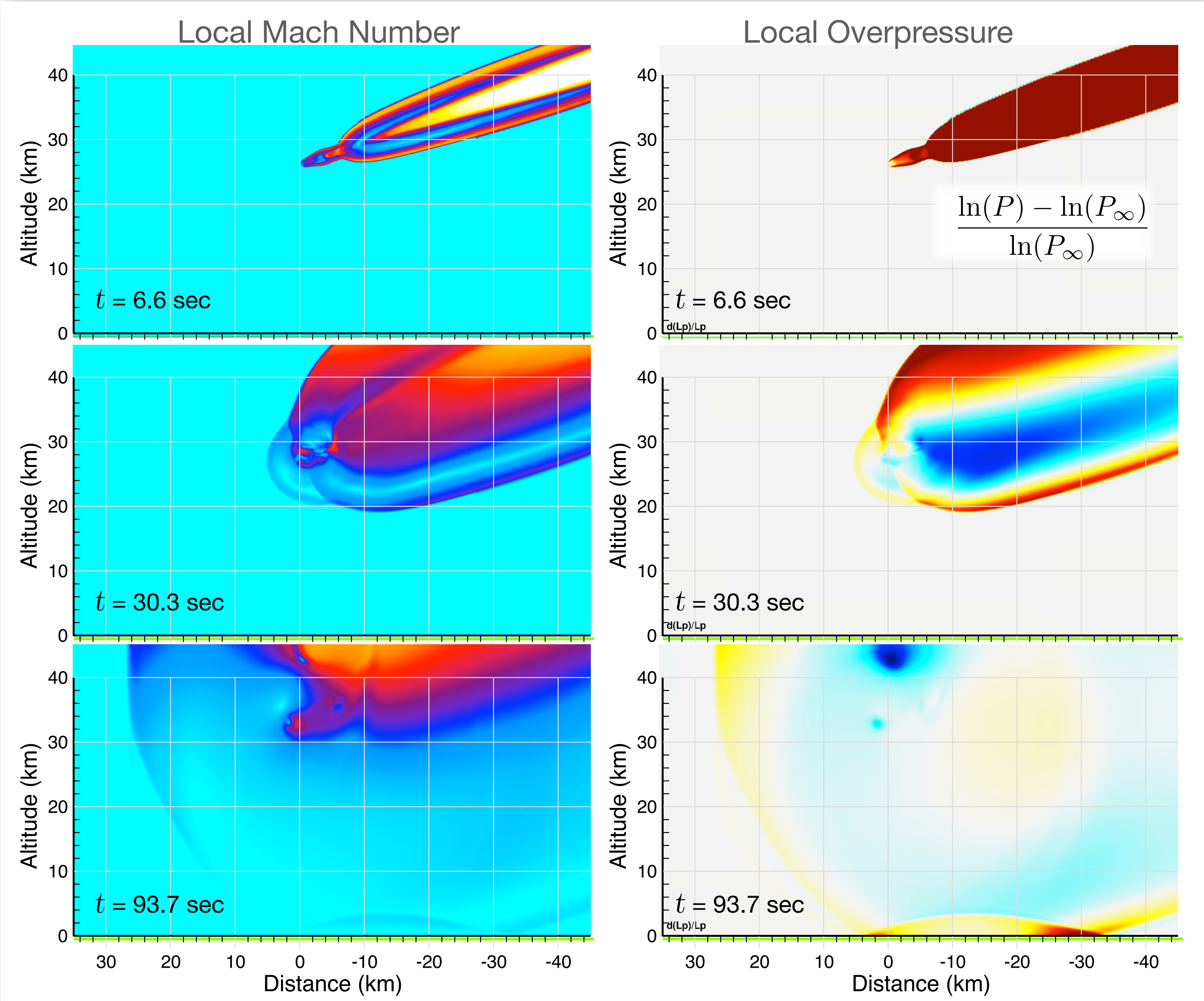
Validation: Chelyabinsk Meteor

Simulation Details

- Energy deposition:
  - E_{tot} = (520 kt – 5% radiation)
  - Profile from Brown et al. Nature 2013
- Net mass deposited:
  - m_{tot} = 12.5e6 kg
- Trajectory:
  - 18.6 km/sec, (~Mach 61.7) @ 18° angle
  - Peak brightness @ 29.5 km
  - ~110 km length, 60→24 km altitude
  - Assume constant velocity
- 3D simulation with ~90M cells
  - Resolution of ~20 m along trajectory & ~100 m resolution near ground
  - Simulation covers ~300 sec. of real time

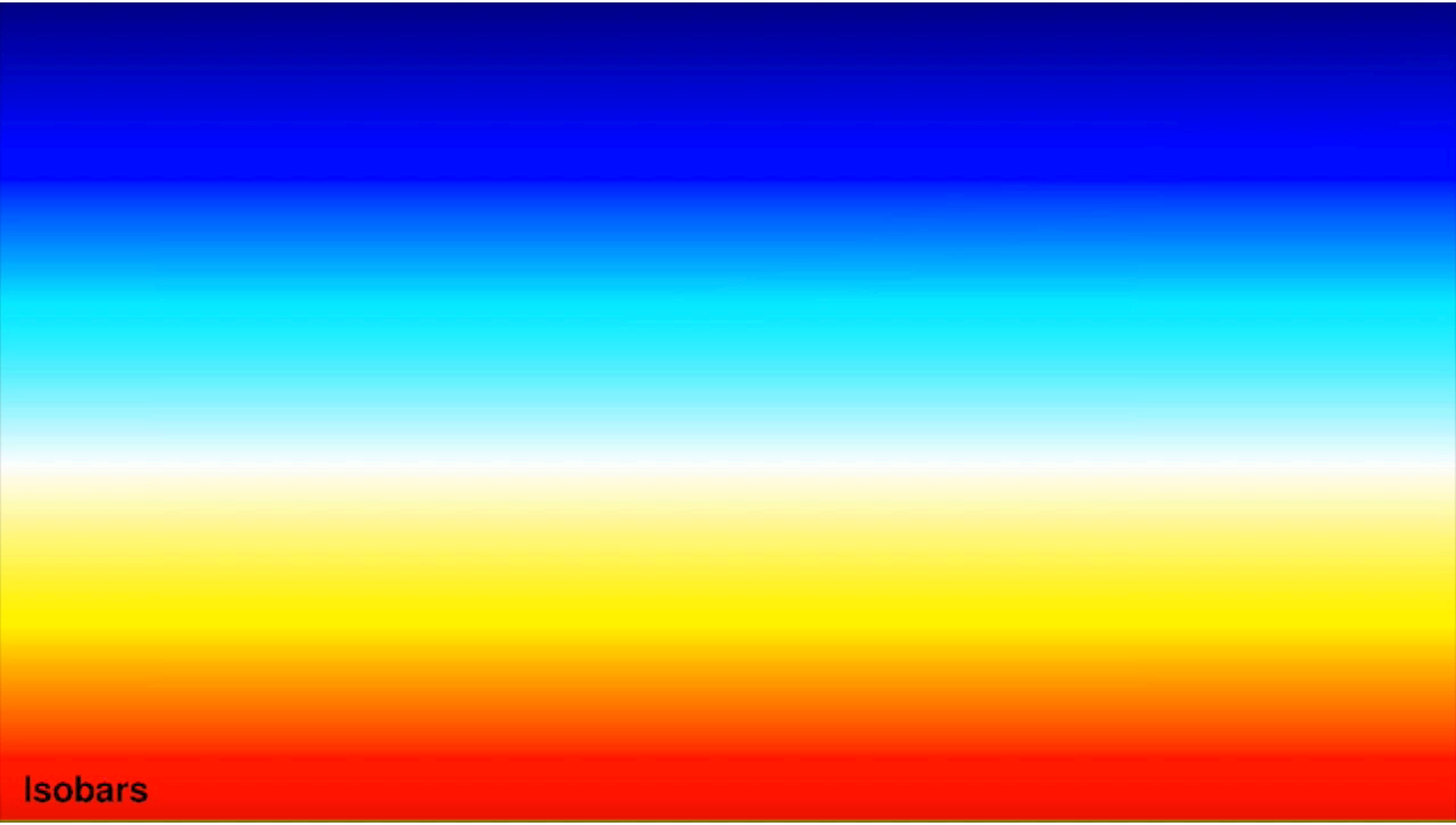






Local Mach Number
Local Overpressure
Altitude (km)
Distance (km)
t = 6.6 sec
t = 30.3 sec
t = 93.7 sec
$$\frac{\ln(P) - \ln(P_\infty)}{\ln(P_\infty)}$$
d(Lp)/Lp

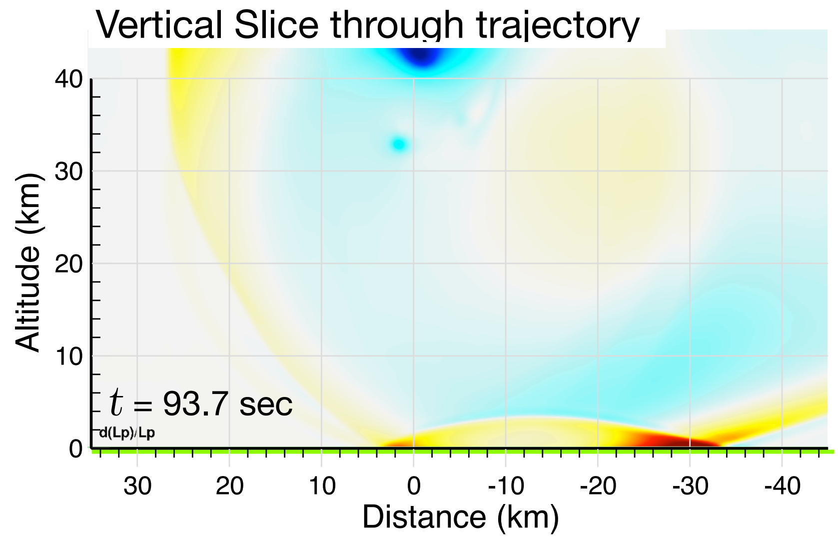
Validation: Chelyabinsk Meteor

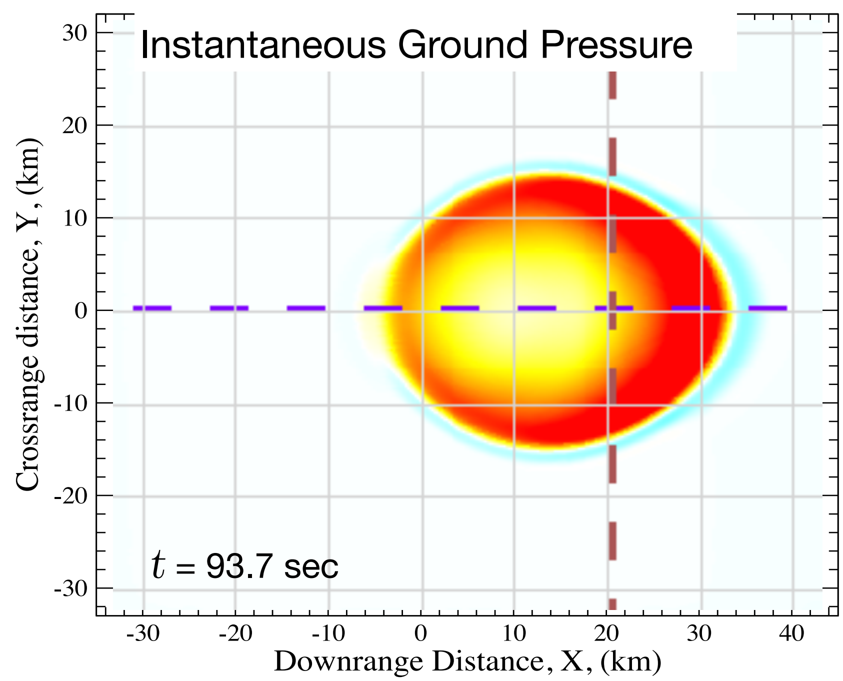


Validation: Chelyabinsk Meteor

Ground footprint

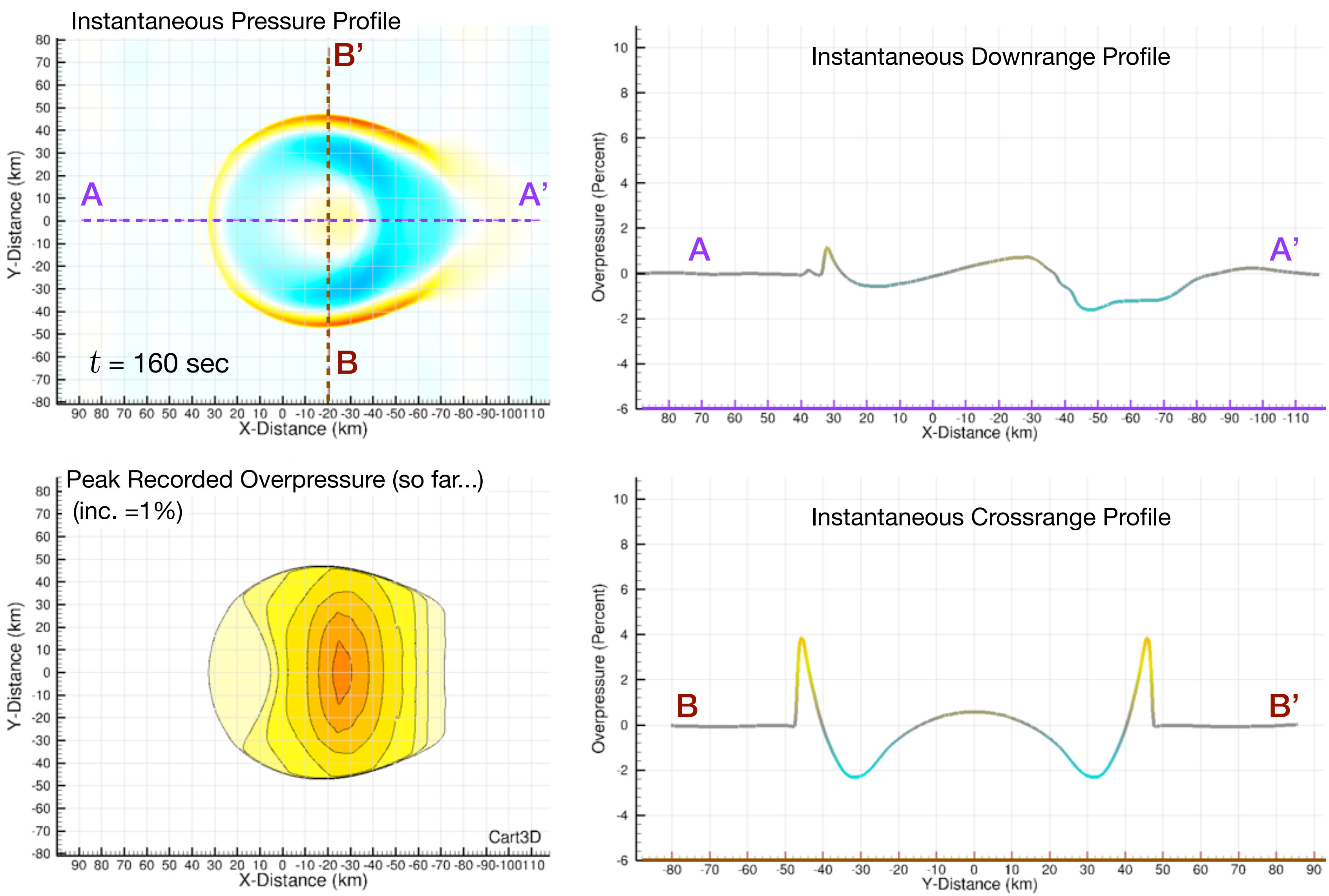
- Goal is prediction of pressure & velocity on the ground
- Blast first contacts ground at $t = \sim 82.7$ sec elapsed time (~77 sec after peak brightness)





Validation: Chelyabinsk Meteor

Ground footprint evolution



Validation: Chelyabinsk Meteor

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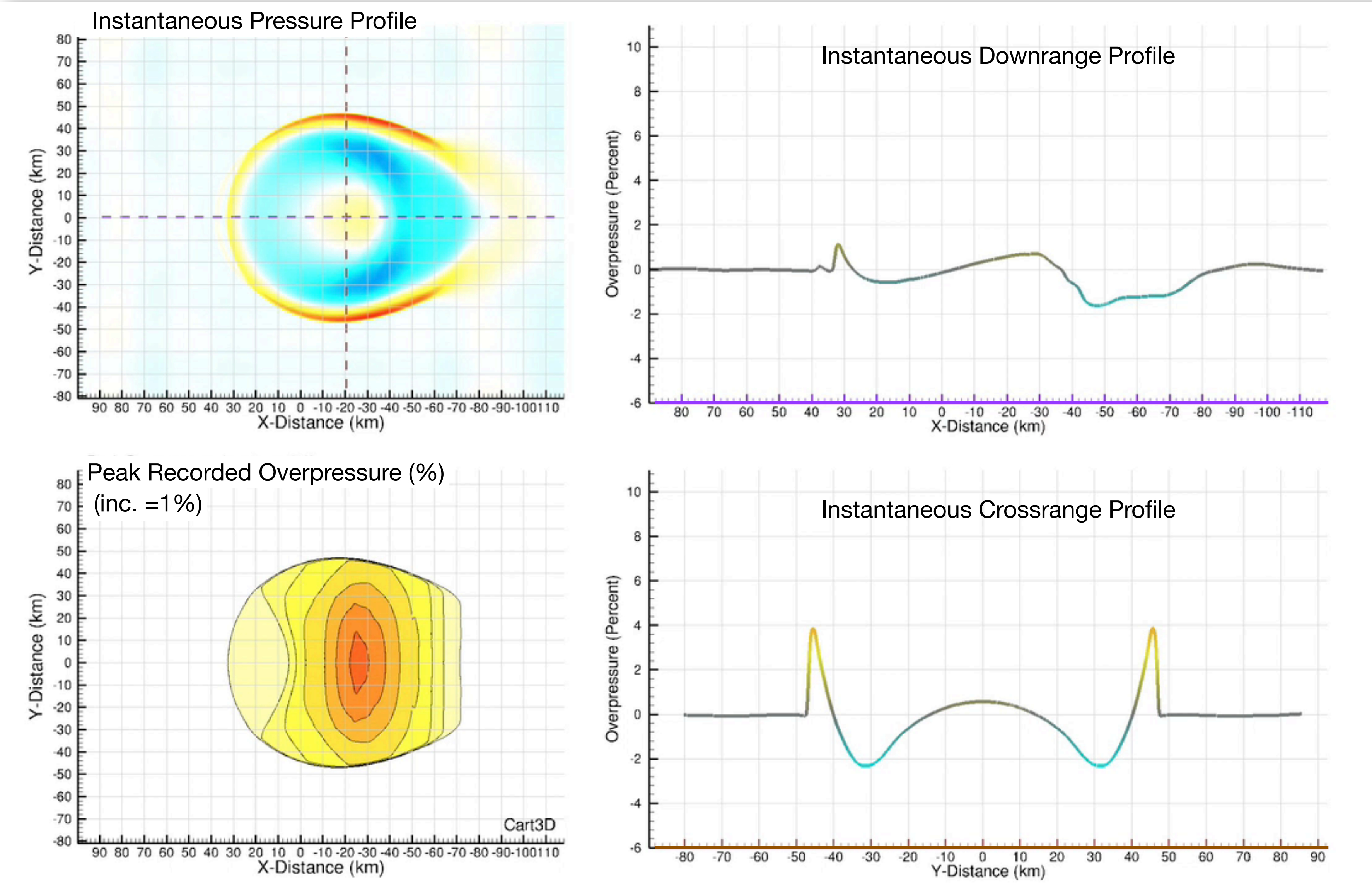
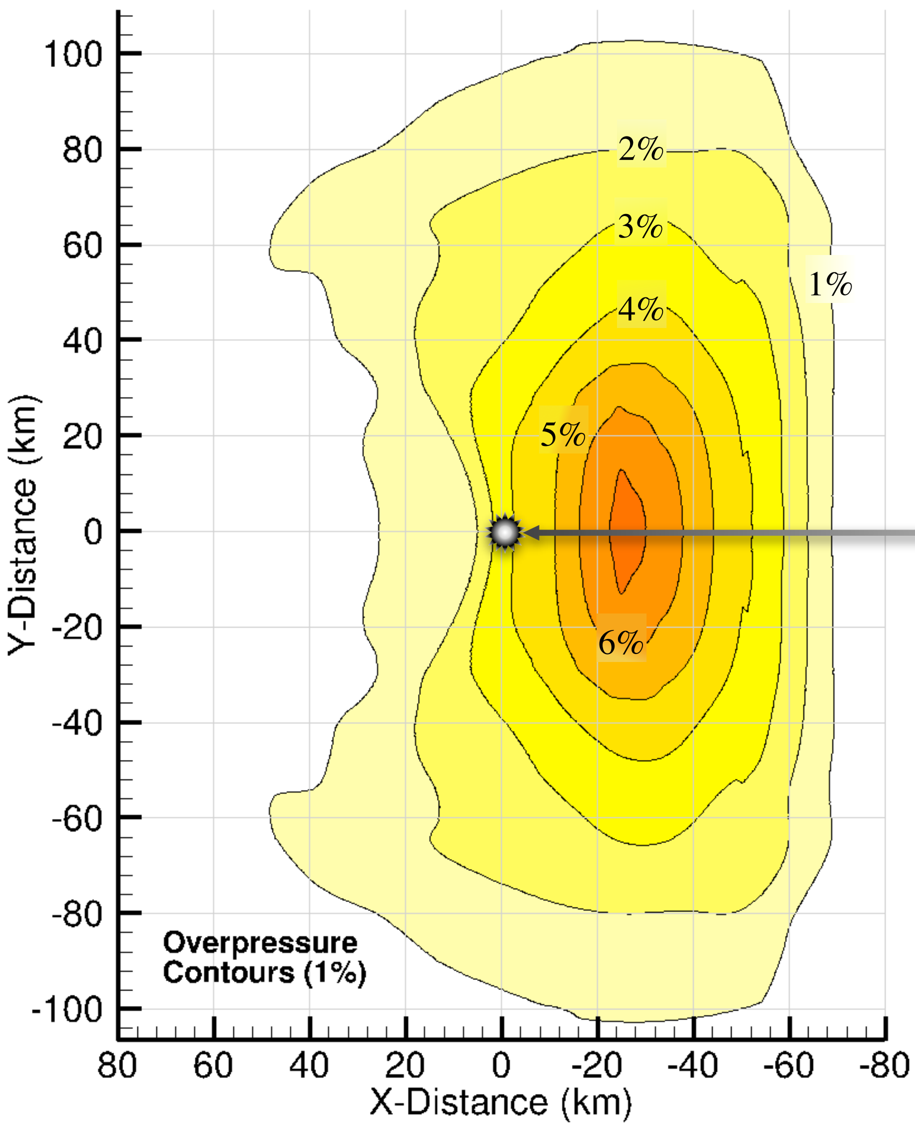
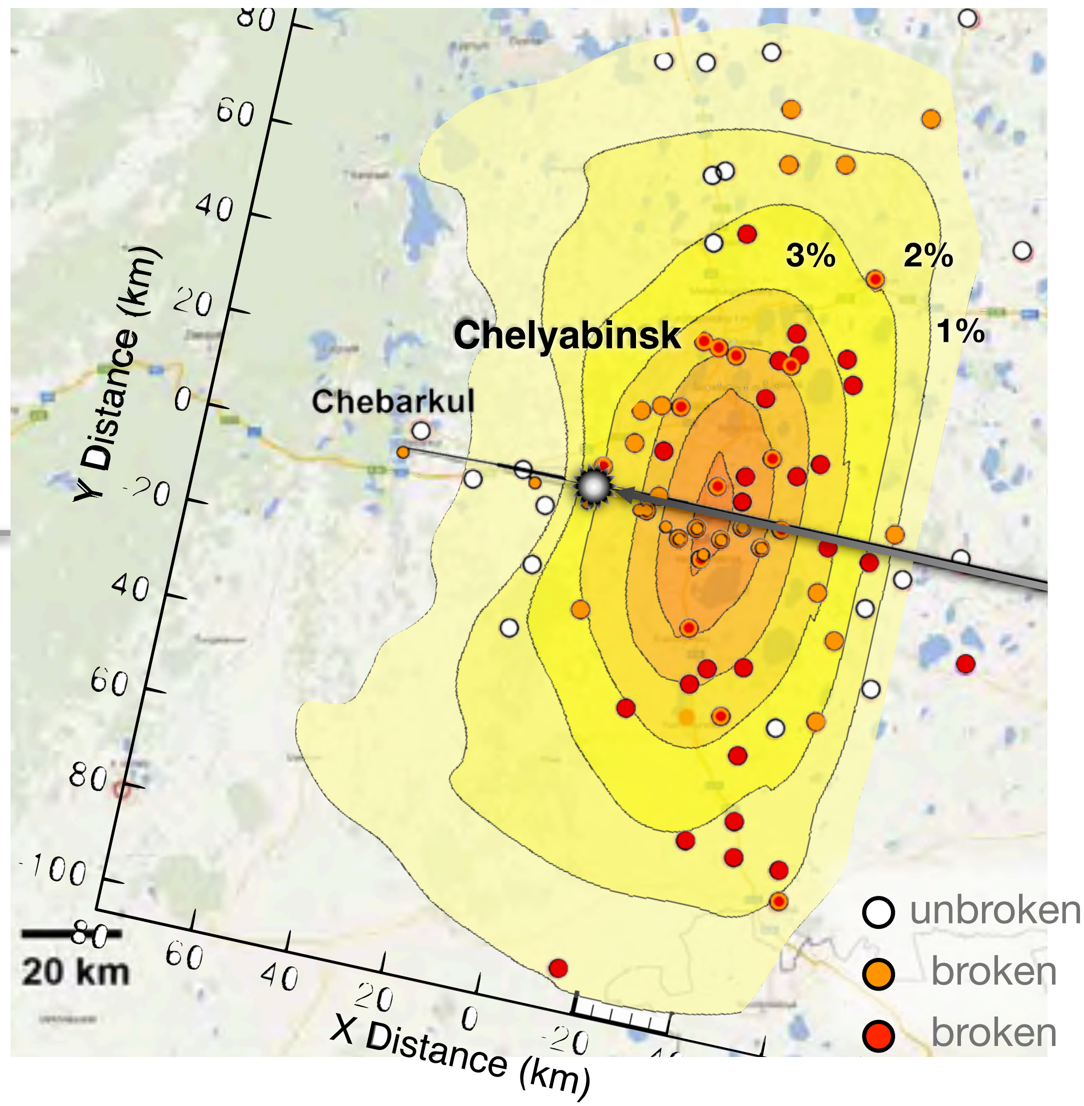


Validation: Chelyabinsk Meteor

Peak Ground Overpressures



Glass damage data collected by the Chelyabinsk Airburst Consortium



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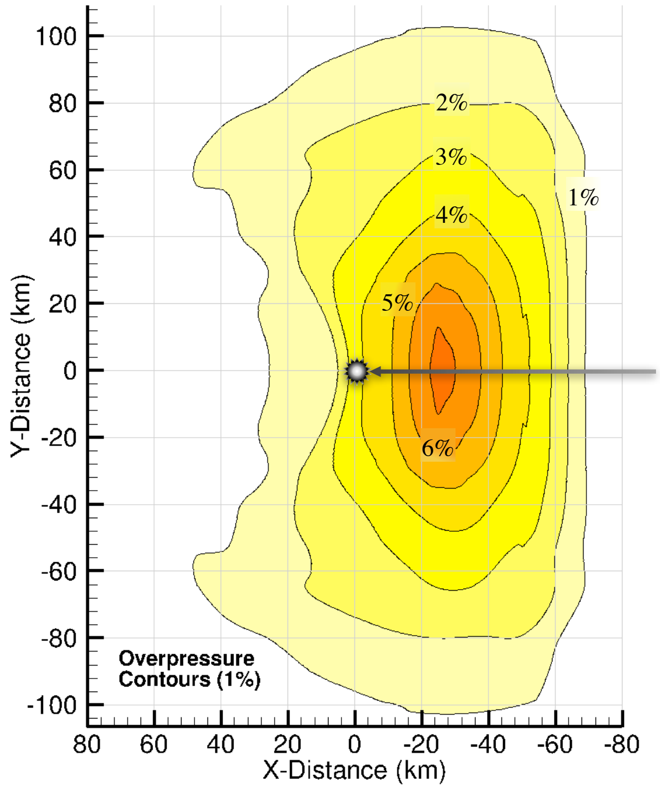

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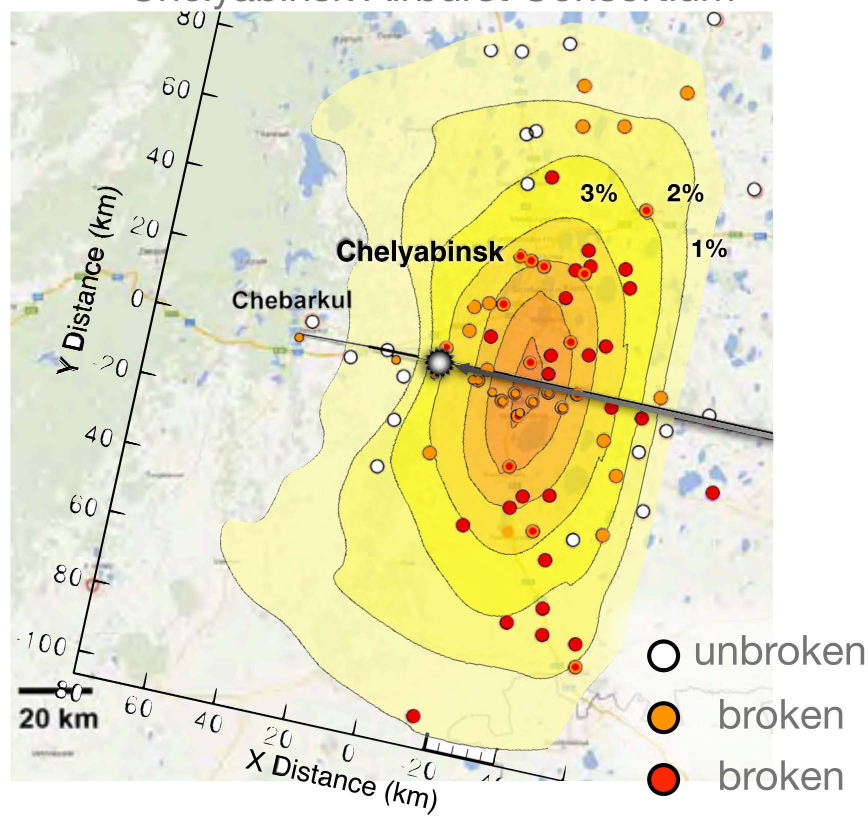

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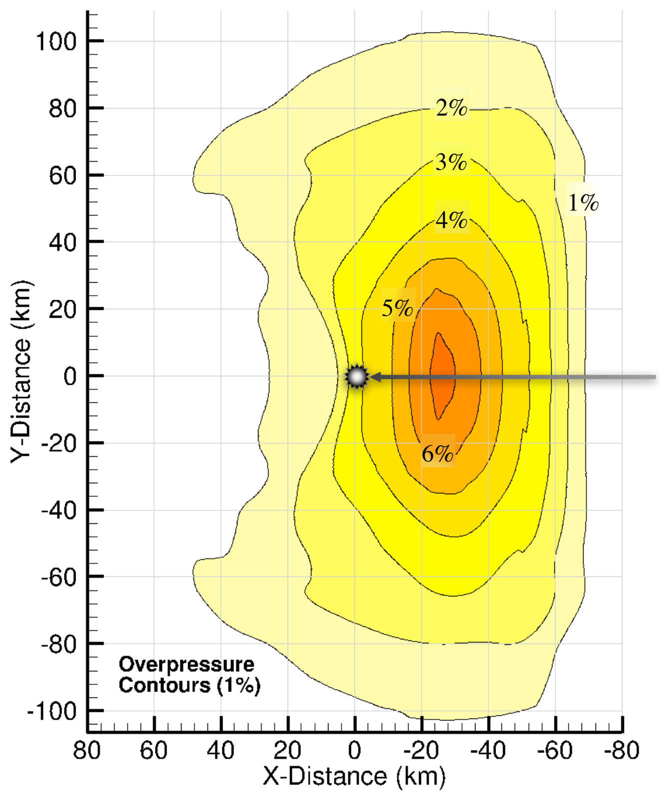

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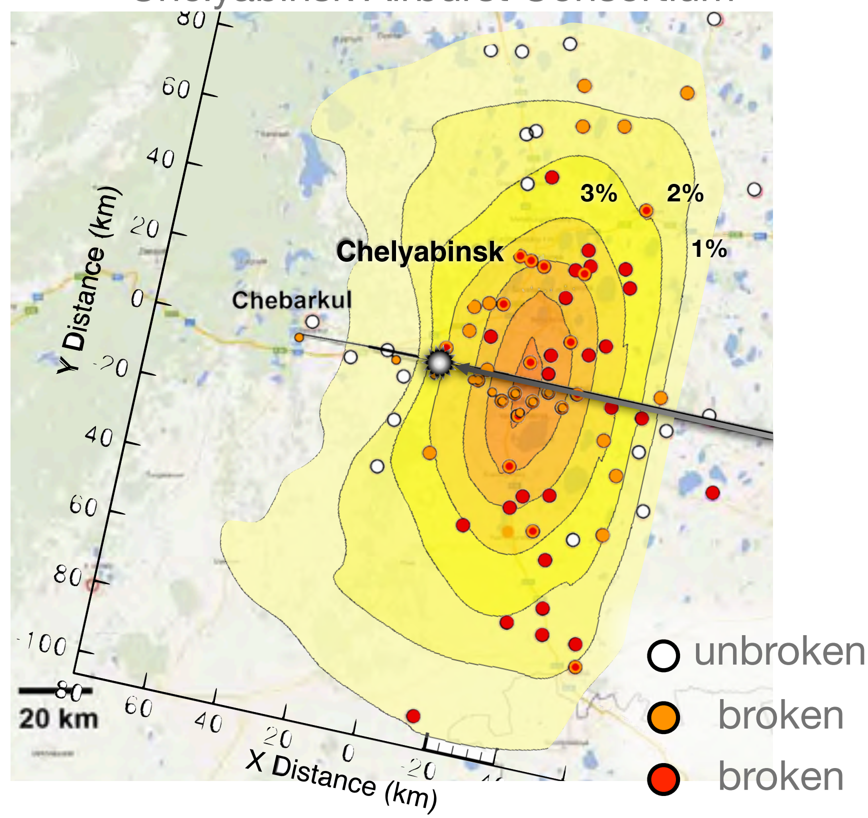
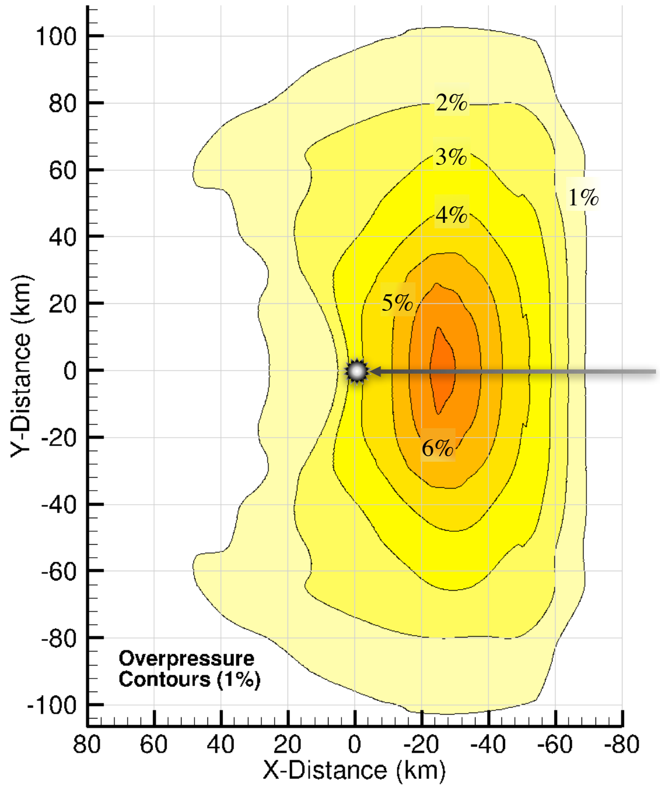


- Statistical correlation (Mannan & Lees) show 700 Pa (0.69%) shatters ~5% of typical windows, 6% overpressure breaks roughly 90%.

Validation: Chelyabinsk Meteor

Peak Ground Overpressures



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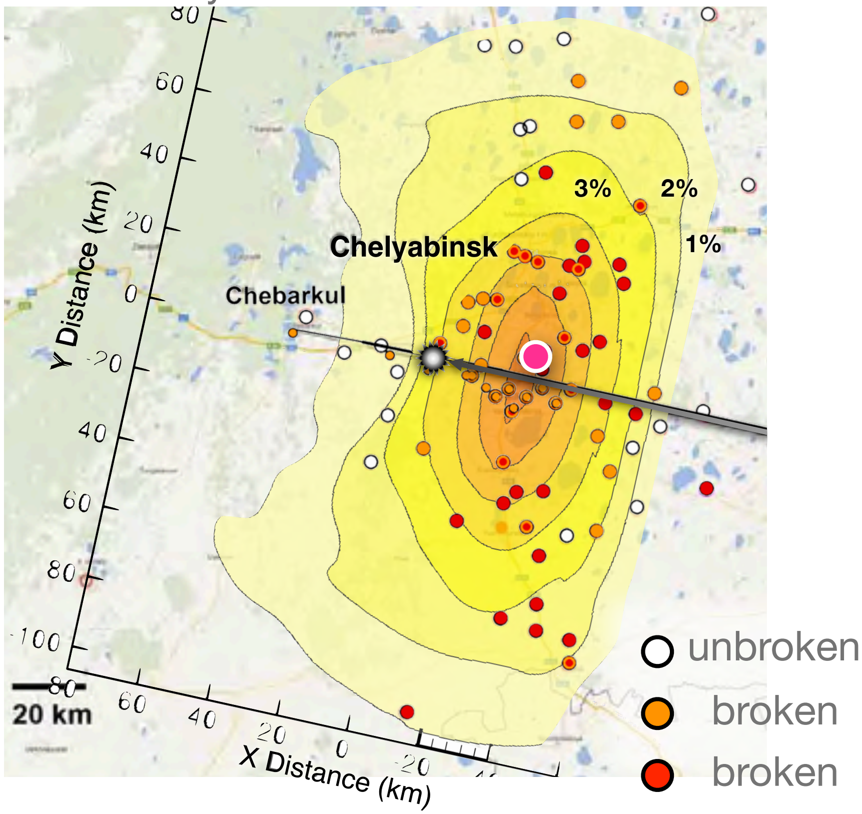
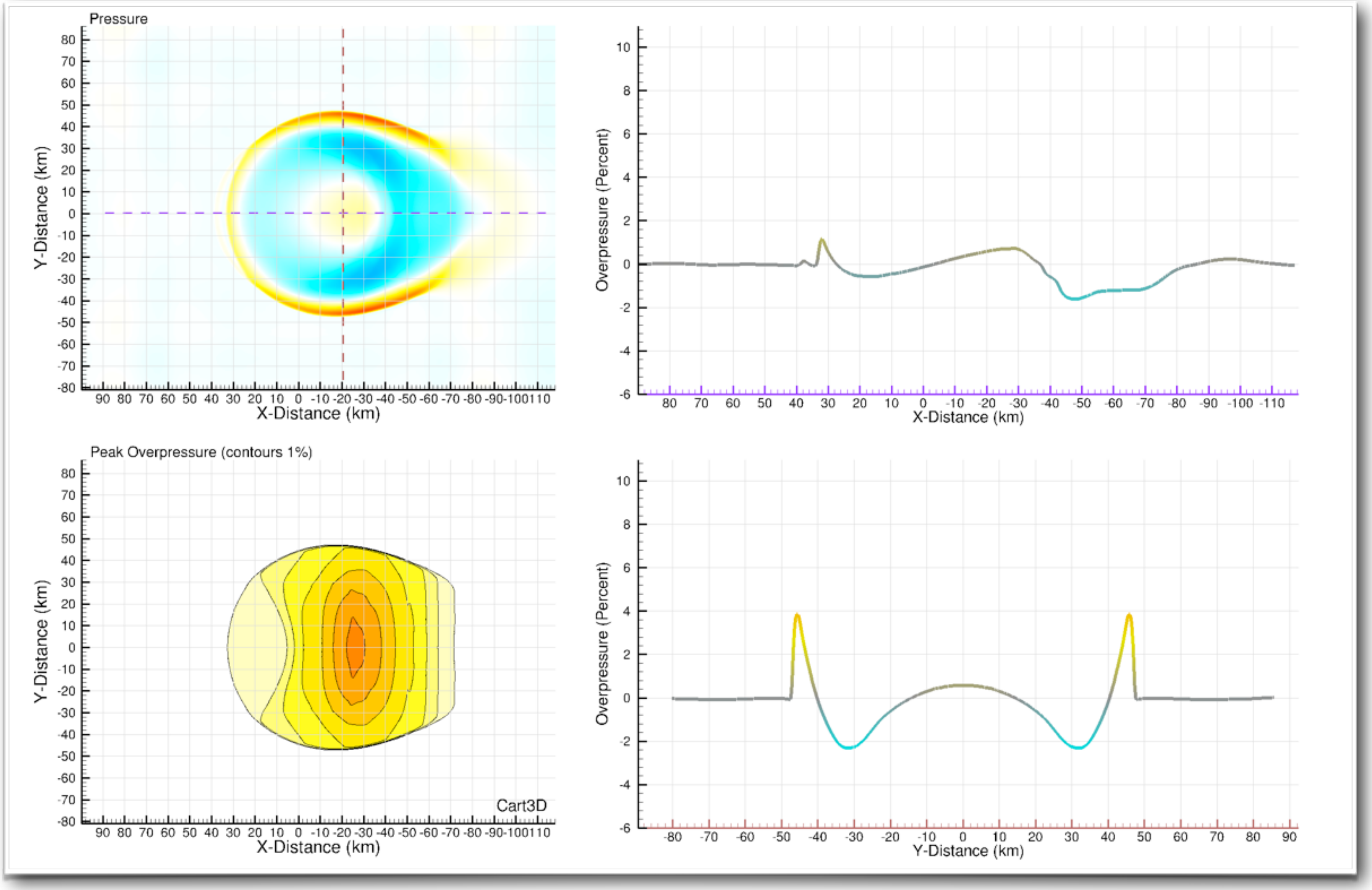


- Statistical correlation (Mannan & Lees) show 700 Pa (0.69%) shatters ~5% of typical windows, 6% overpressure breaks roughly 90%.
- Korkino had highest injury per capita, located 6-7 km from highest predicted overpressure
- Best estimate for overpressure at Chelyabinsk from data ~2-4% (P. Brown, UWO)
- Footprint similar to those in Popova et al. (ScienceExpress)

Validation: Chelyabinsk Meteor

Shock Arrival Time



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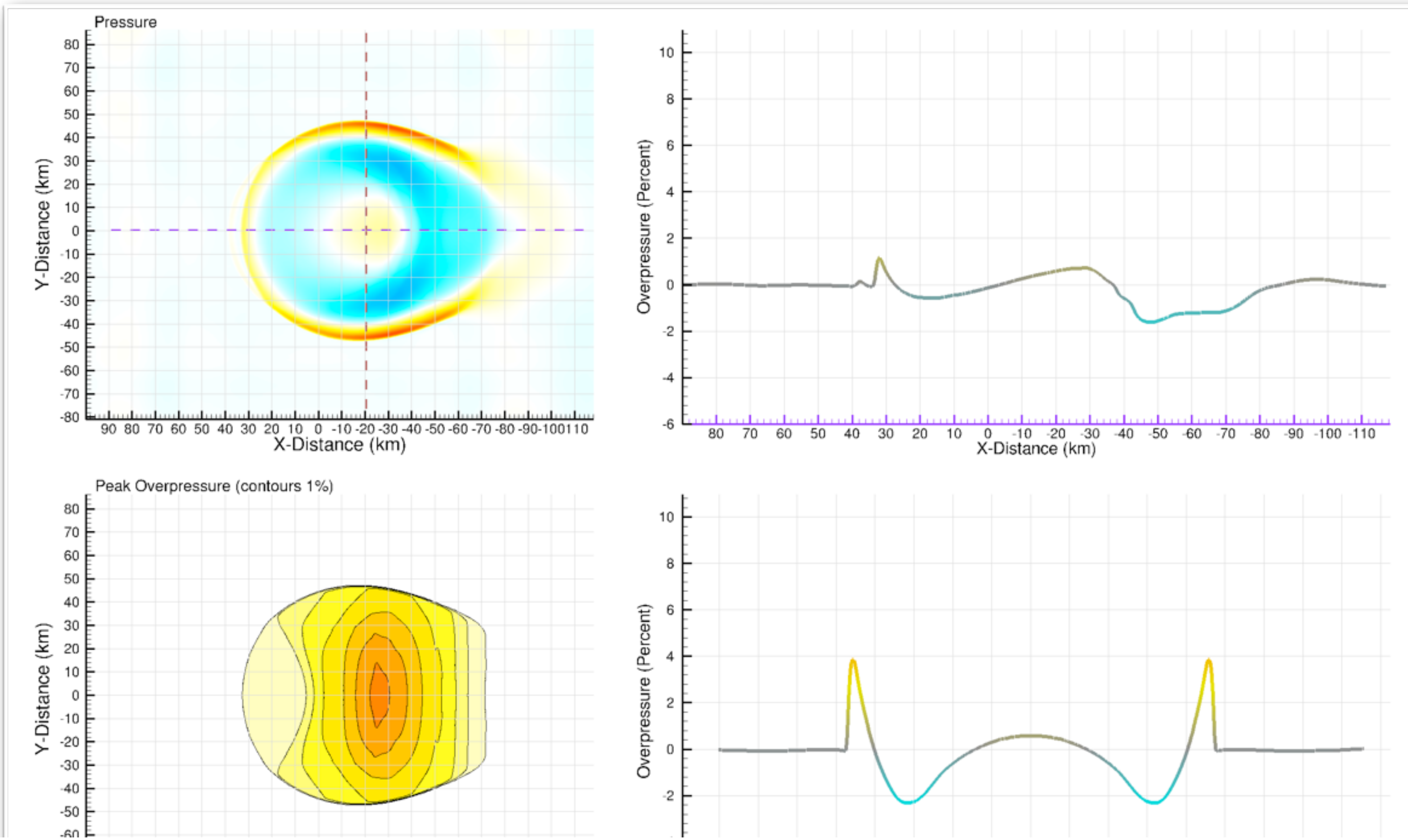

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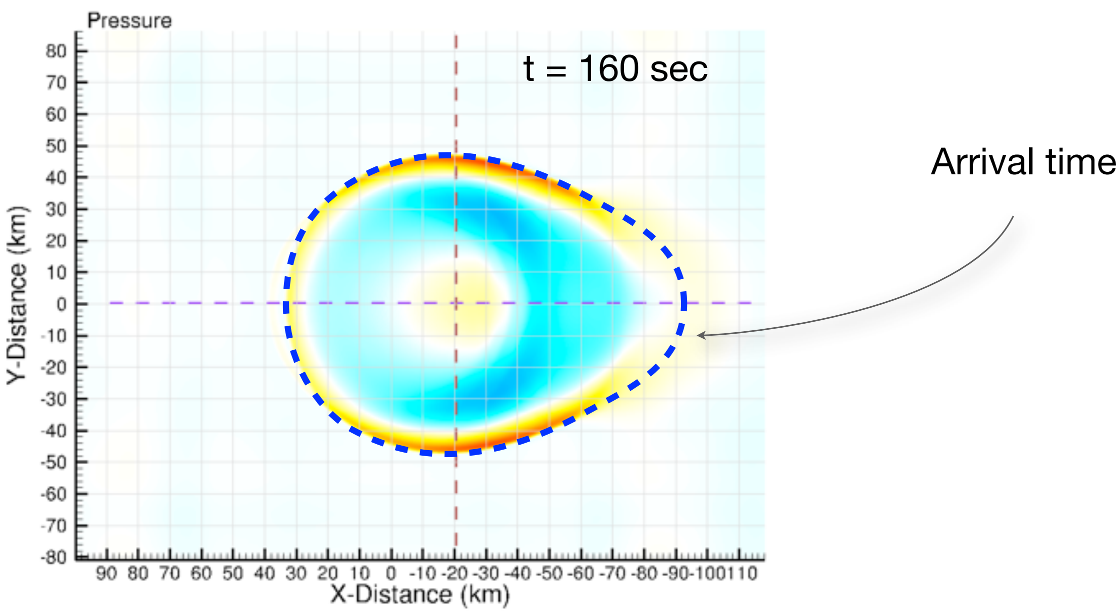
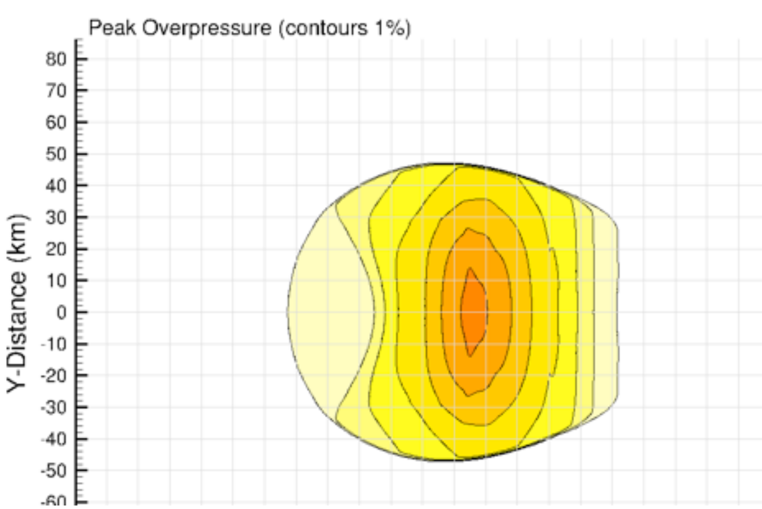
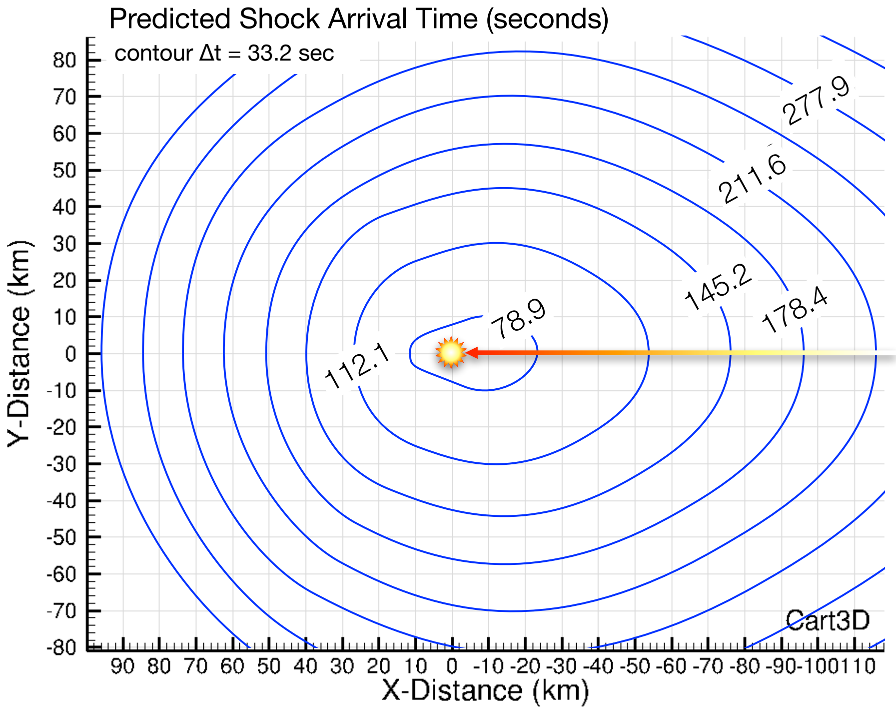




Validation: Chelyabinsk Meteor

Shock Arrival Time



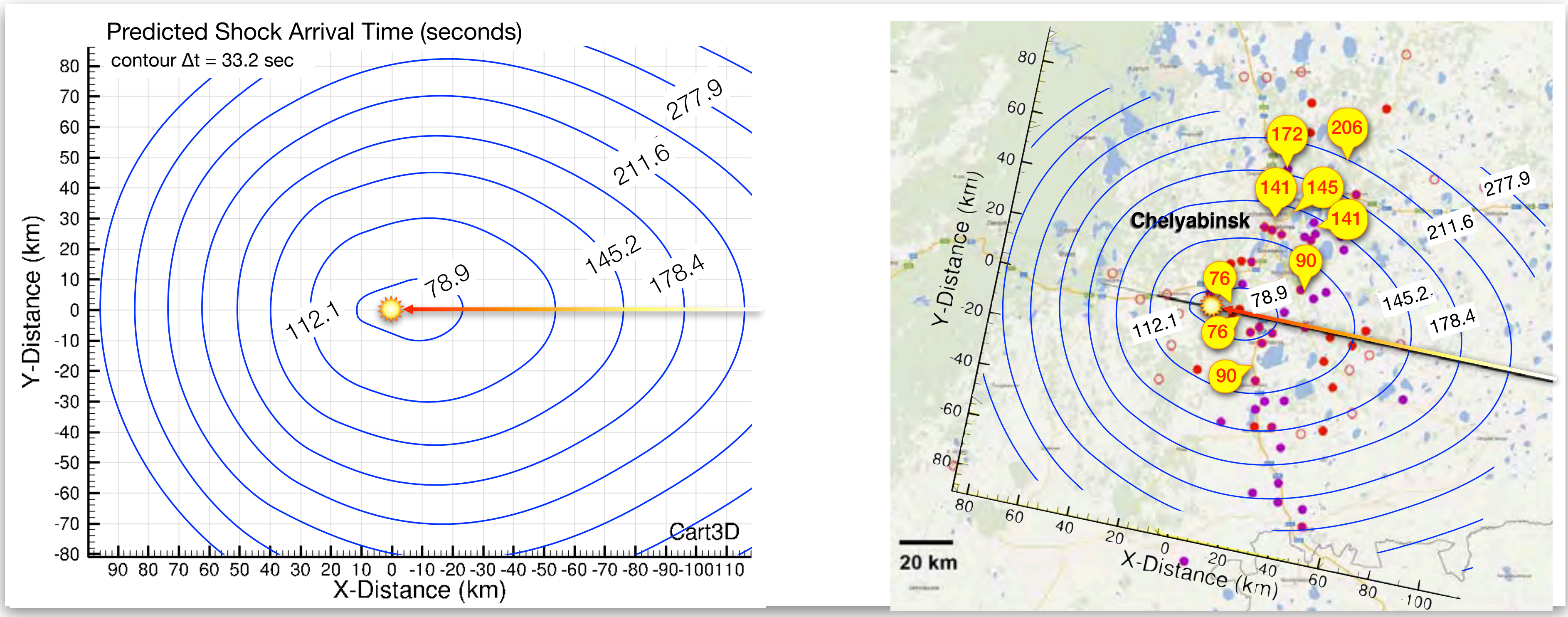
Blast arrival time data

- Mostly from video evidence
- Quite reliable since many have time data synchronized through internet/cell-service or the flash from peak brightness

Validation: Chelyabinsk Meteor

Shock Arrival Time

Elapsed Time (sec) from peak brightness

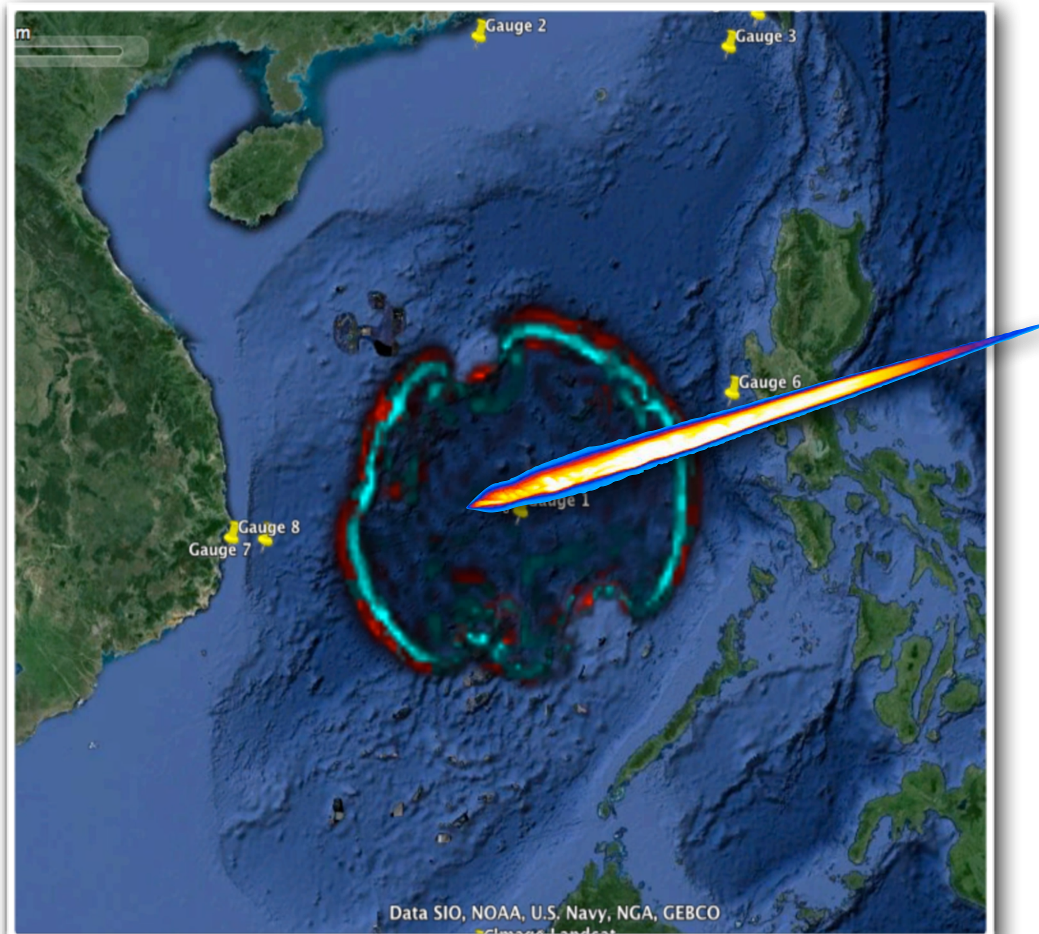


- First arrival at ~77 sec after peak brightness,
- Predict ~90 sec (from peak brightness) at Korkino and Yemanzhelinsk
- Arrival in vicinity of Chelyabinsk at 140 - 145 seconds
- Neglected local wind, temperature and other effects of the real atmosphere
- Overall very good agreement with data & best predictions in literature

Overview

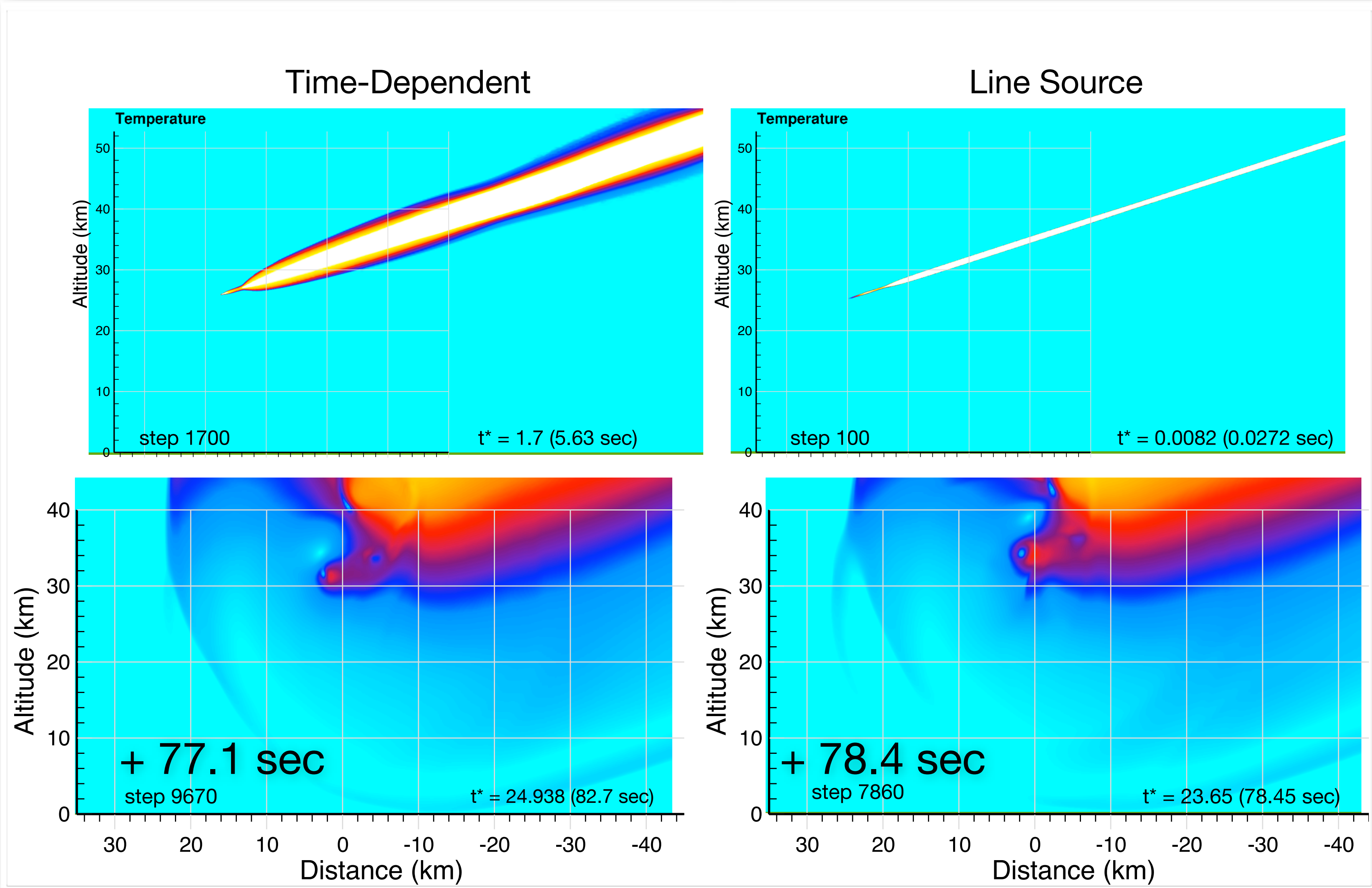
Report current status of effort and connection with PRA and tsunami

- Modeling tools & solver
- Entry & airburst modeling
  - Energy deposition model
  - Chelyabinsk Case Study
- Ground-footprint sensitivity
  - Line-source vs time-dependent
  - Entry angle & spherical blast
- Upcoming Efforts
  - Tsunami prediction



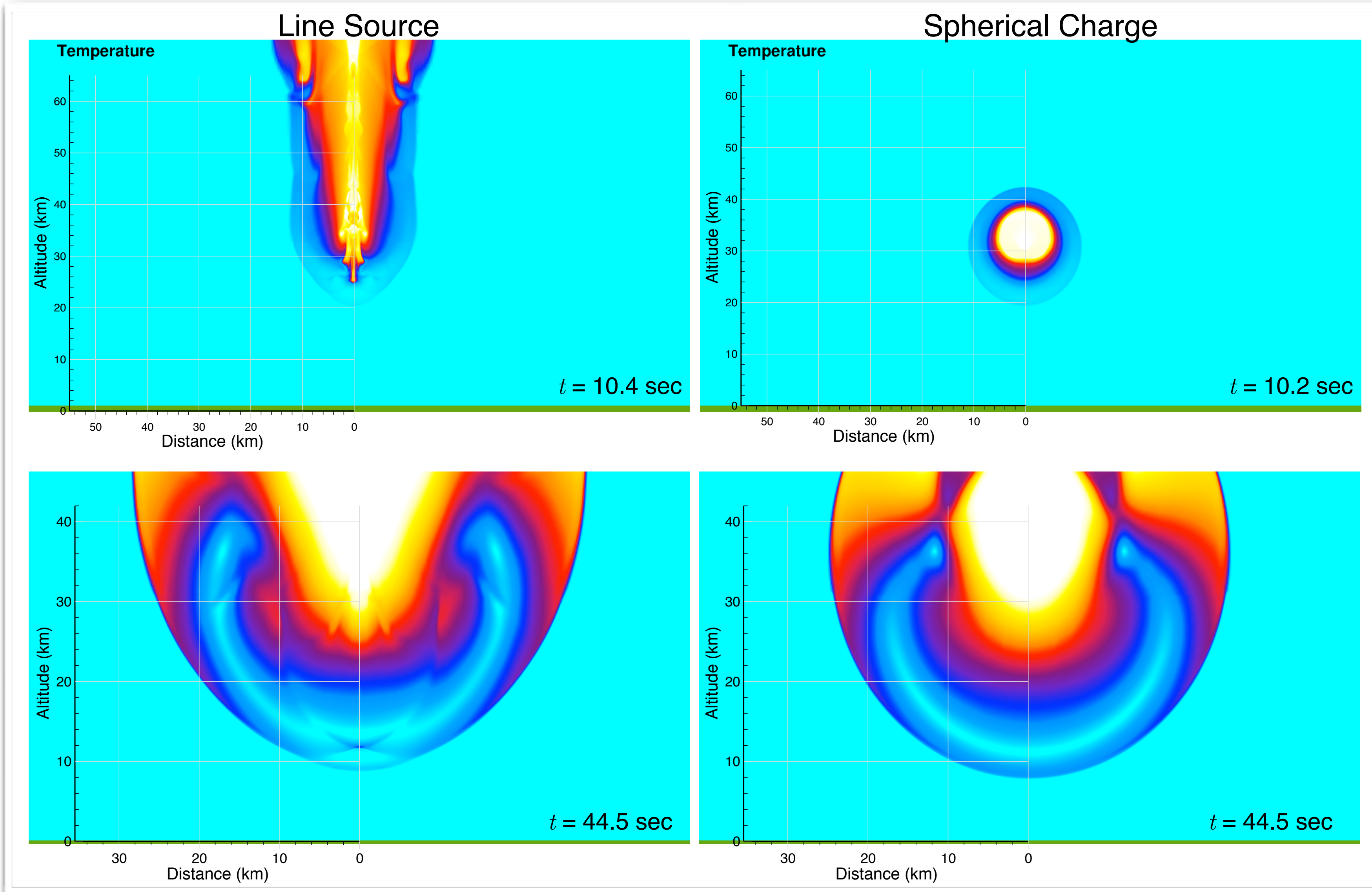
Sensitivity - Entry Modeling

Time-dependent vs line source – See AIAA 2016-0998...



Sensitivity - 90° Entry vs Spherical Charge

See paper...



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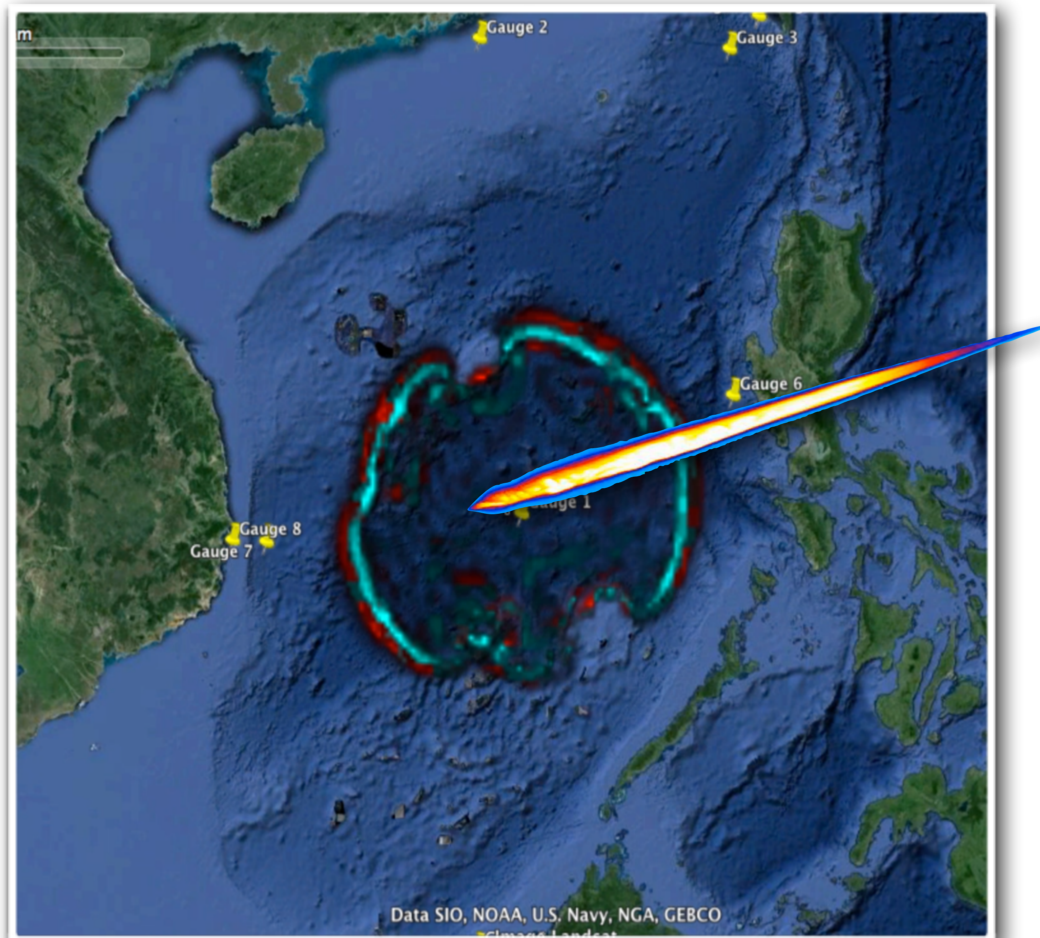
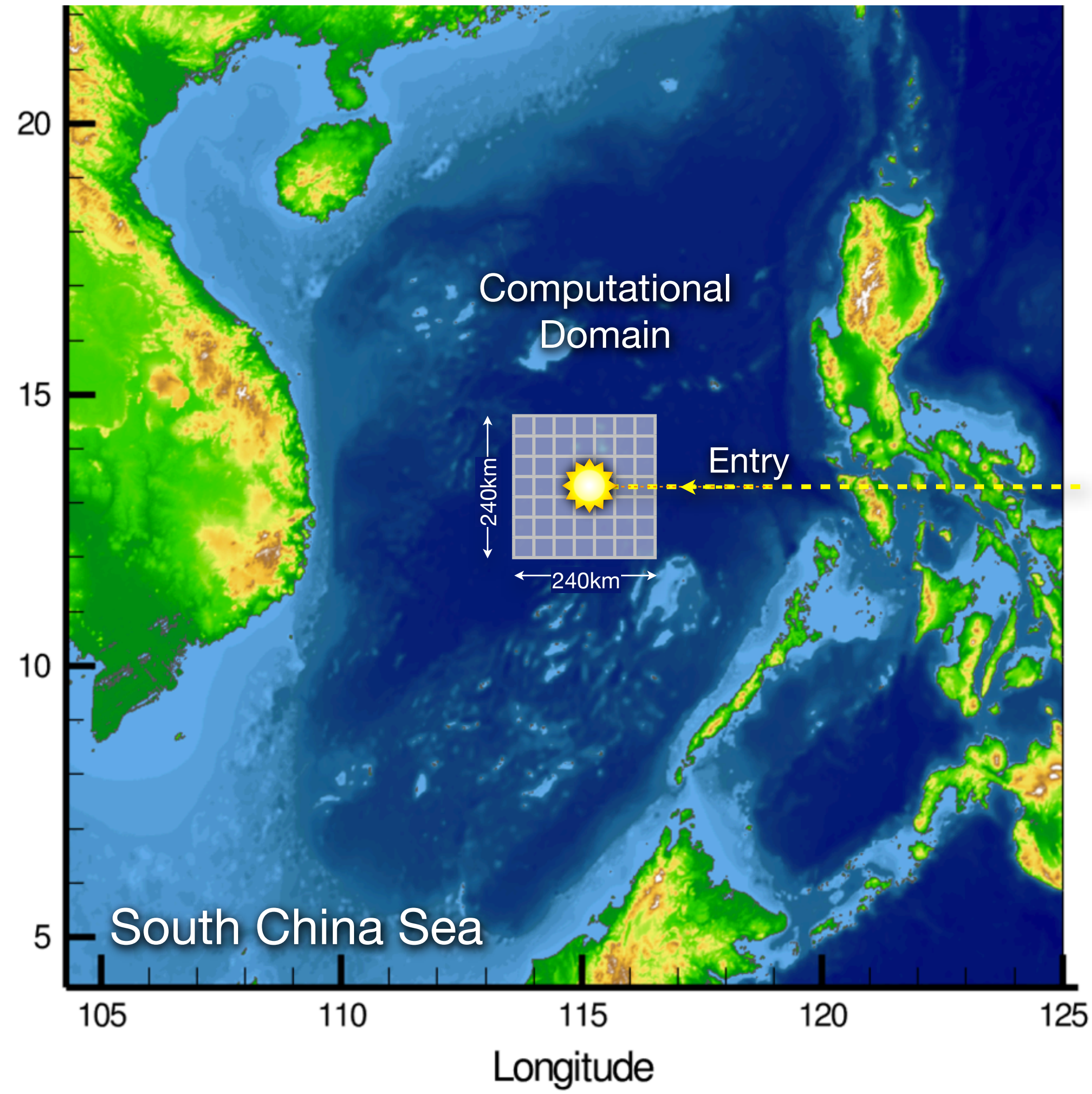


M. Berger

Preliminary Effort on Tsunami Coupling

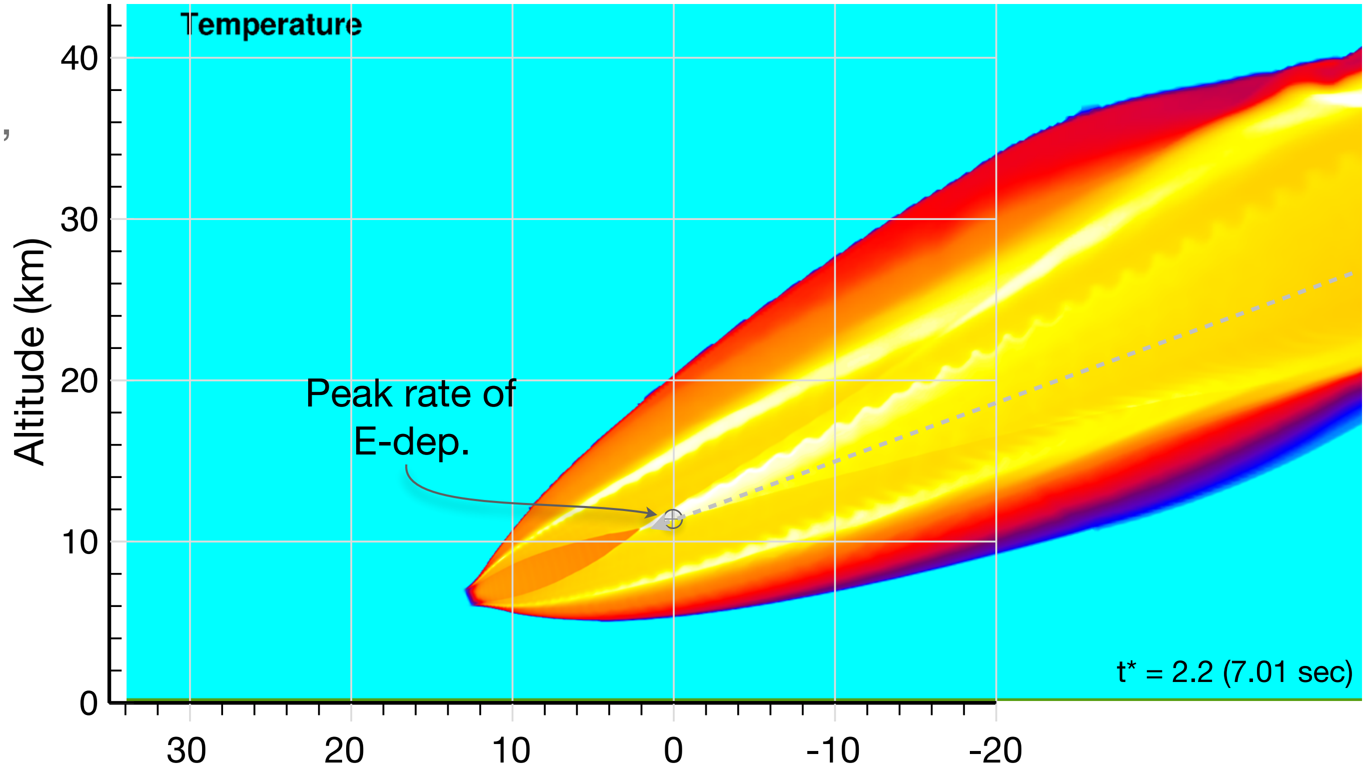
Couple surface overpressure and wind to drive ocean surface

- Entry over water may trigger tsunami
- Risk – tsunami can turn a regional event into a global catastrophe
- Scales:
  - Meteor entry - seconds
  - Air Propagation - minutes
  - Tsunami Propagation - hours
- Workshop planned for Aug. 2016 aimed at quantifying risk
- Preliminary results



Energy Deposition

- Largest "reasonable" airburst, E_{Tot} = 662 MT TNT equiv. ~ Magnitude 9.1 earthquake ~ 45000 yr intermittency
- Incoming asteroid has:
  - Diam = 200m
  - V = 20km/sec @ 20°∠
  - ρ = 3300 kg/m^3
- Trajectory:
  - Starts @ 54km
  - M_∞ = 63.76
  - Covers 157.9 km, 20°∠
  - Extends to sea level



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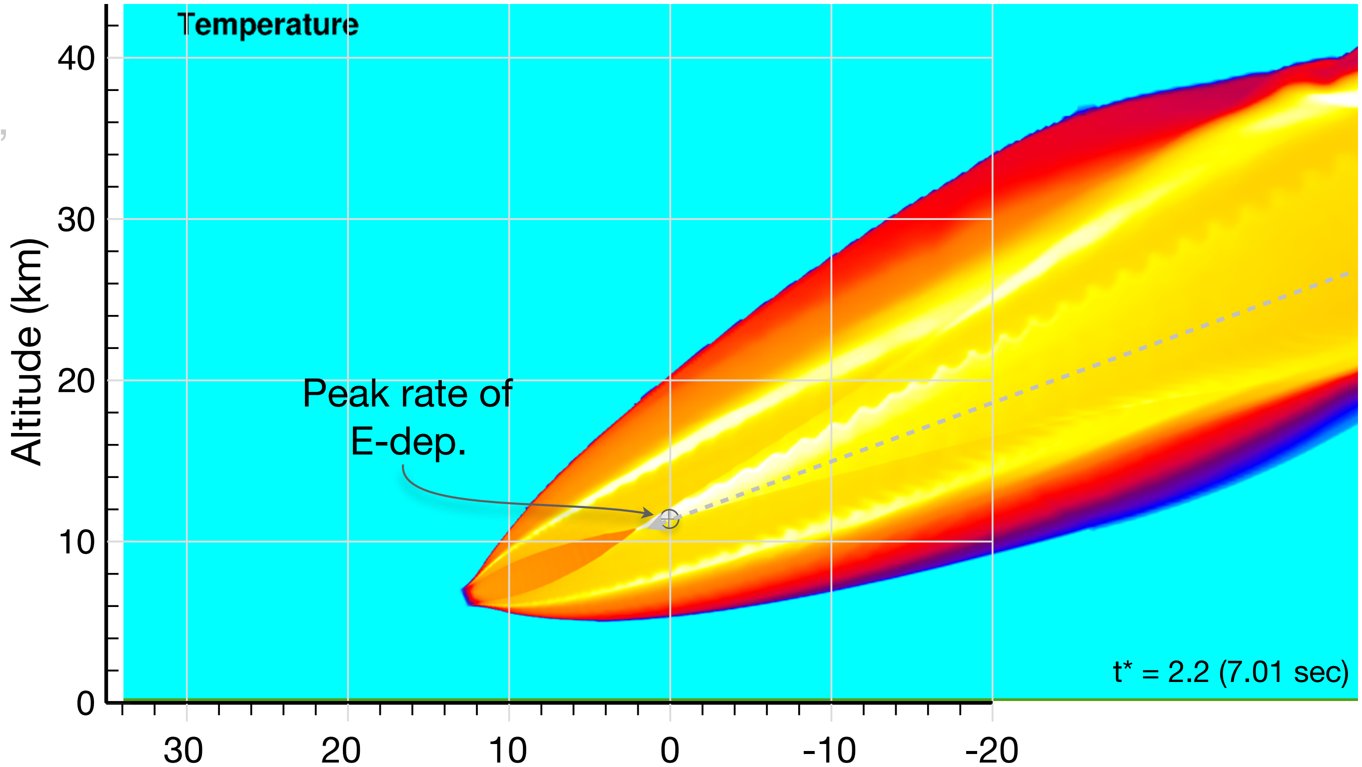
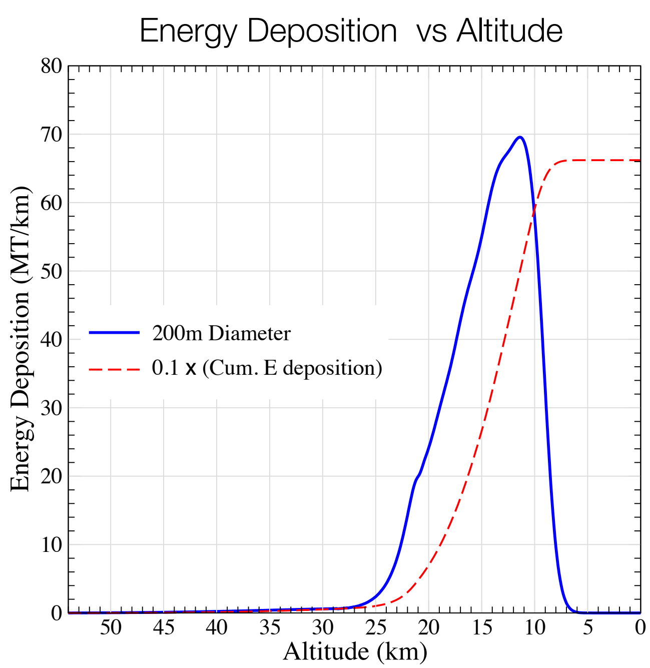
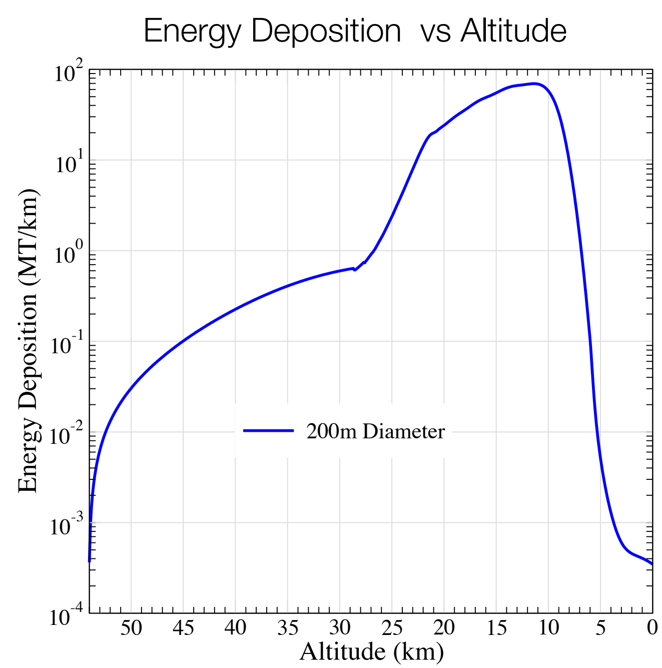
  - Starts @ 54km
  - M_∞ = 63.76
  - Covers 157.9 km, 20°∠
  - Extends to sea level

- Peak Energy-deposition is ~70MT/km, @ ~11.4 km (34,000 ft)
- Some mass survives to ground (~0.4kT/km)
- Isothermal power-law atmosphere model, T_∞ = 245K



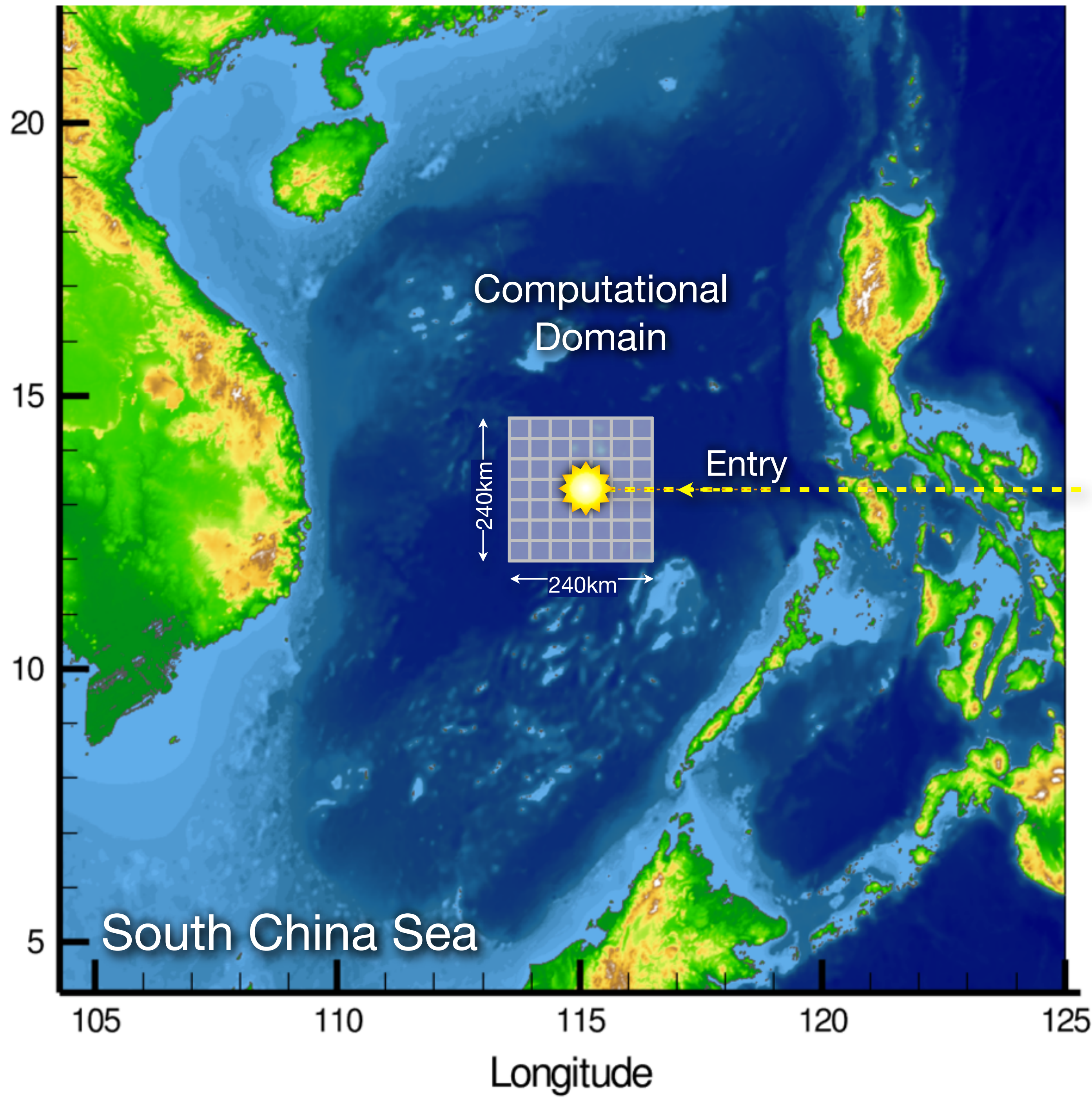




Far-Field Propagation

South China Sea

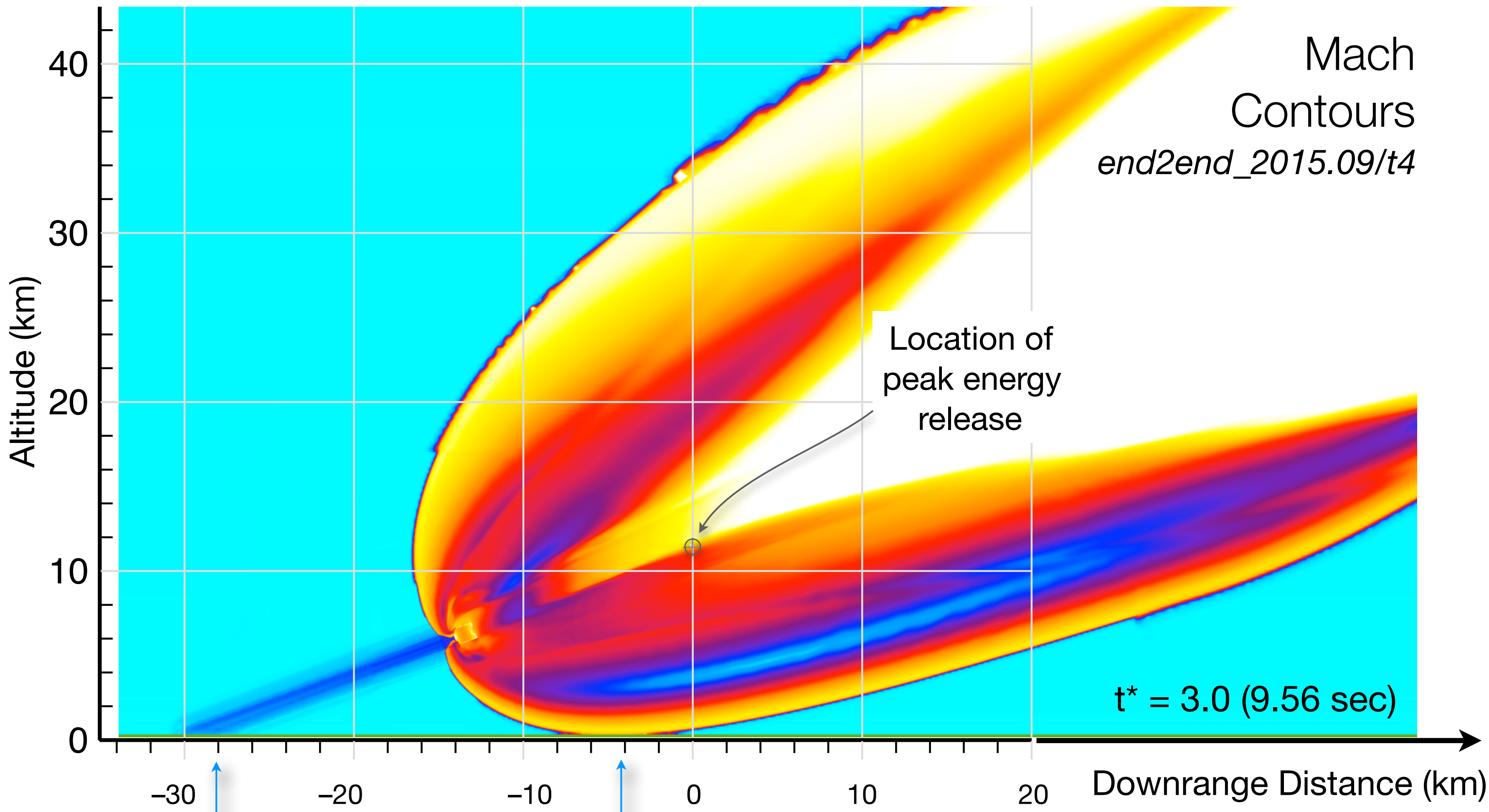
- Domain Extent:
  240 x 240 x 80 km high
  ~58,000 km^2 of surface
- ~105 M total cells
- 20 m resolution along trajectory,
- 80 m resolution at sea level
- 3D time-dependent simulations using Cart3D
- Resources
  (1000 cores x ~12 hrs) on NASA's Pleiades system



Propagation

Snapshot at time of first blast wave arrival at sea level

D = 200m, V = 20km/sec, ϕ = 20°, ρ = 3300 kg/m³, E_{Tot} = 662 MT tnt equiv.



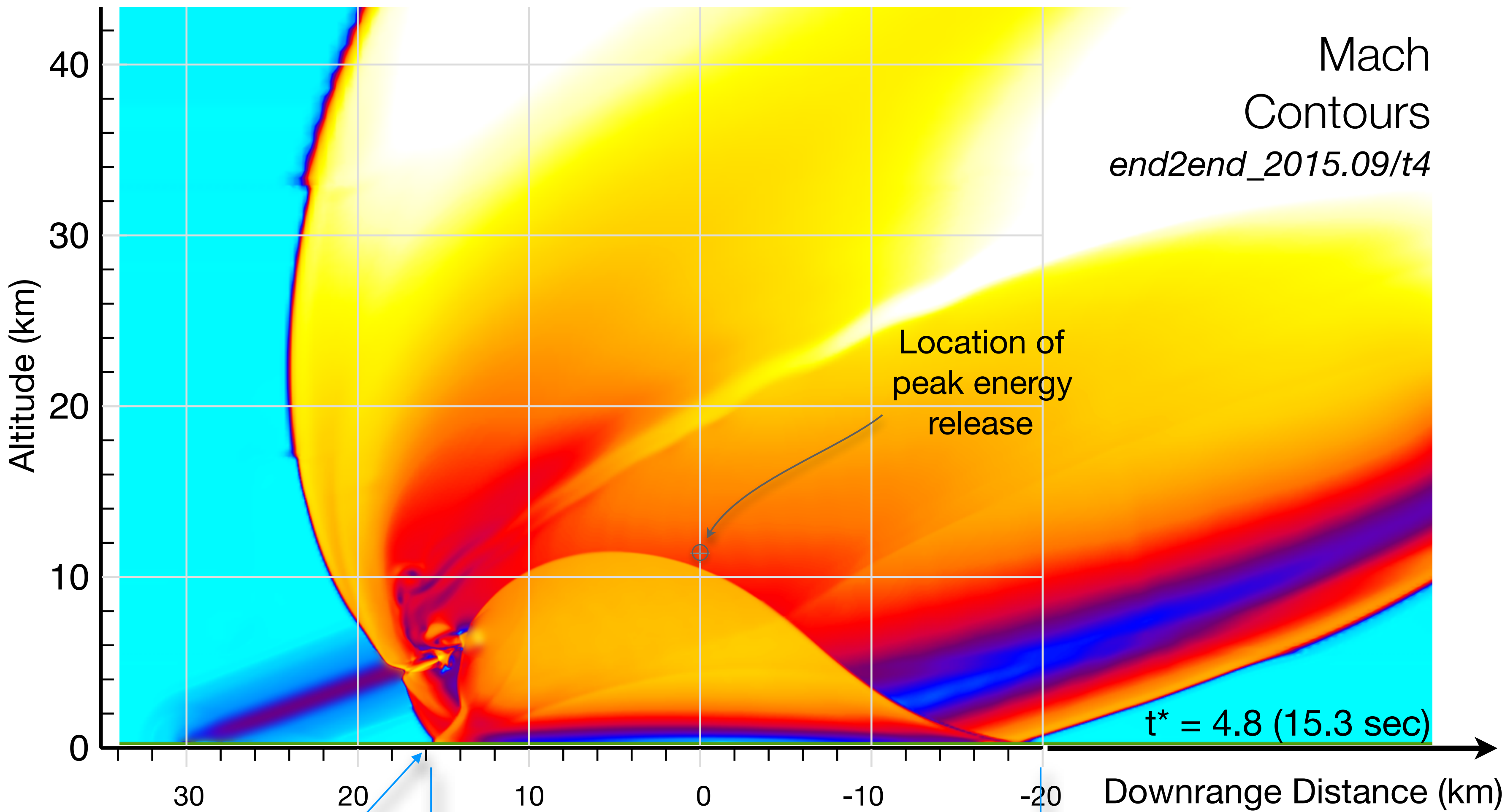
Remaining fragments arrive roughly at the same time as blast

First arrival of blast wave ~3.4 sec after peak brightness

Propagation

Snapshot of Blast Evolution

D = 200m, V = 20km/sec, ϕ = 20°, ρ = 3300 kg/m^3, E_{Tot} = 662 MT tnt equiv.



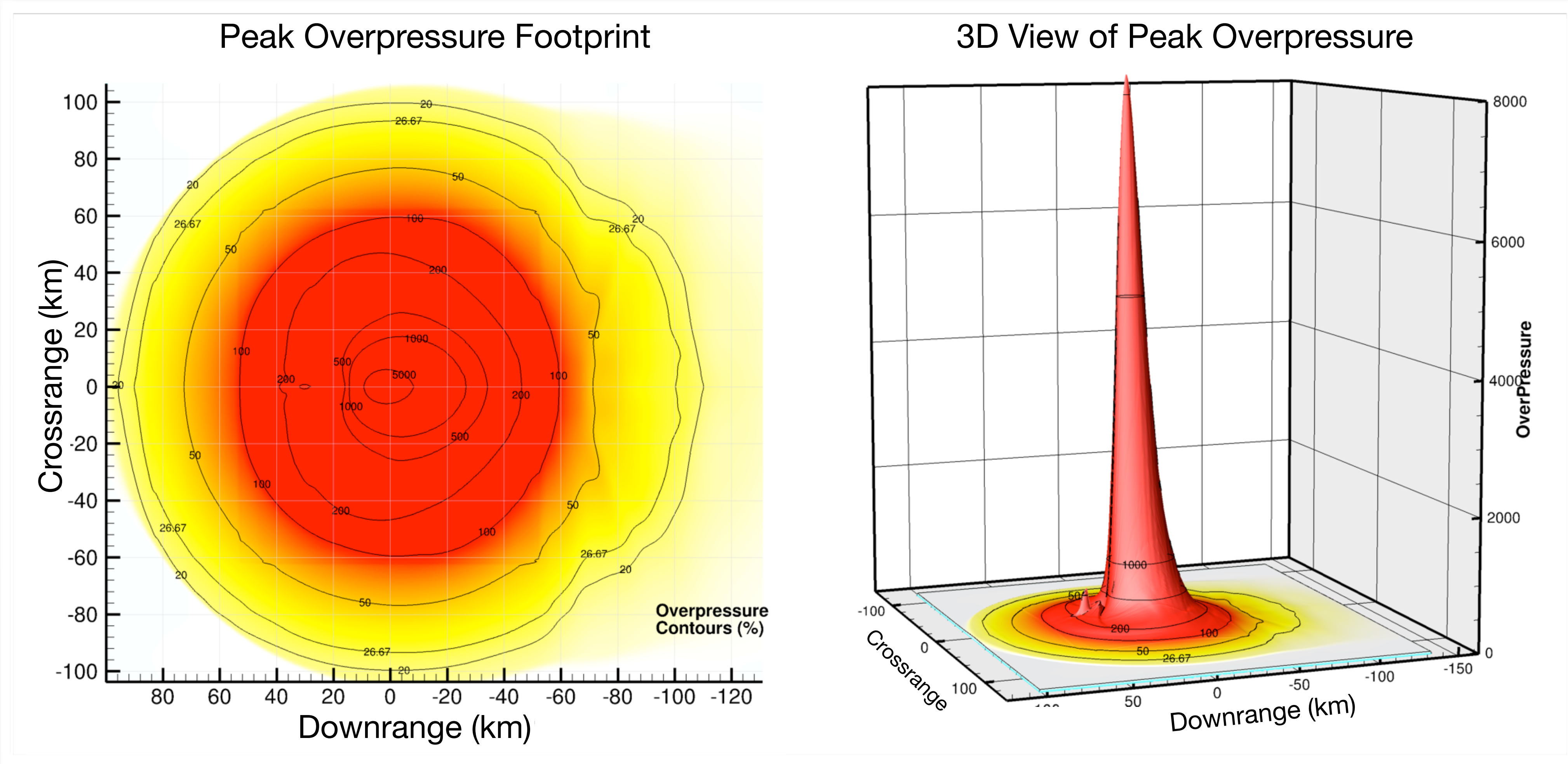
Mach stem forms in downrange and crossflow directions

Blast covers over 1000 km^2 10 seconds after peak brightness

Ground Overpressure

Recording of Peak Overpressure at Sea Level

D = 200m, V = 20km/sec, ϕ = 20°, ρ = 3300 kg/m^3, E_{Tot} = 662 MT tnt equiv.

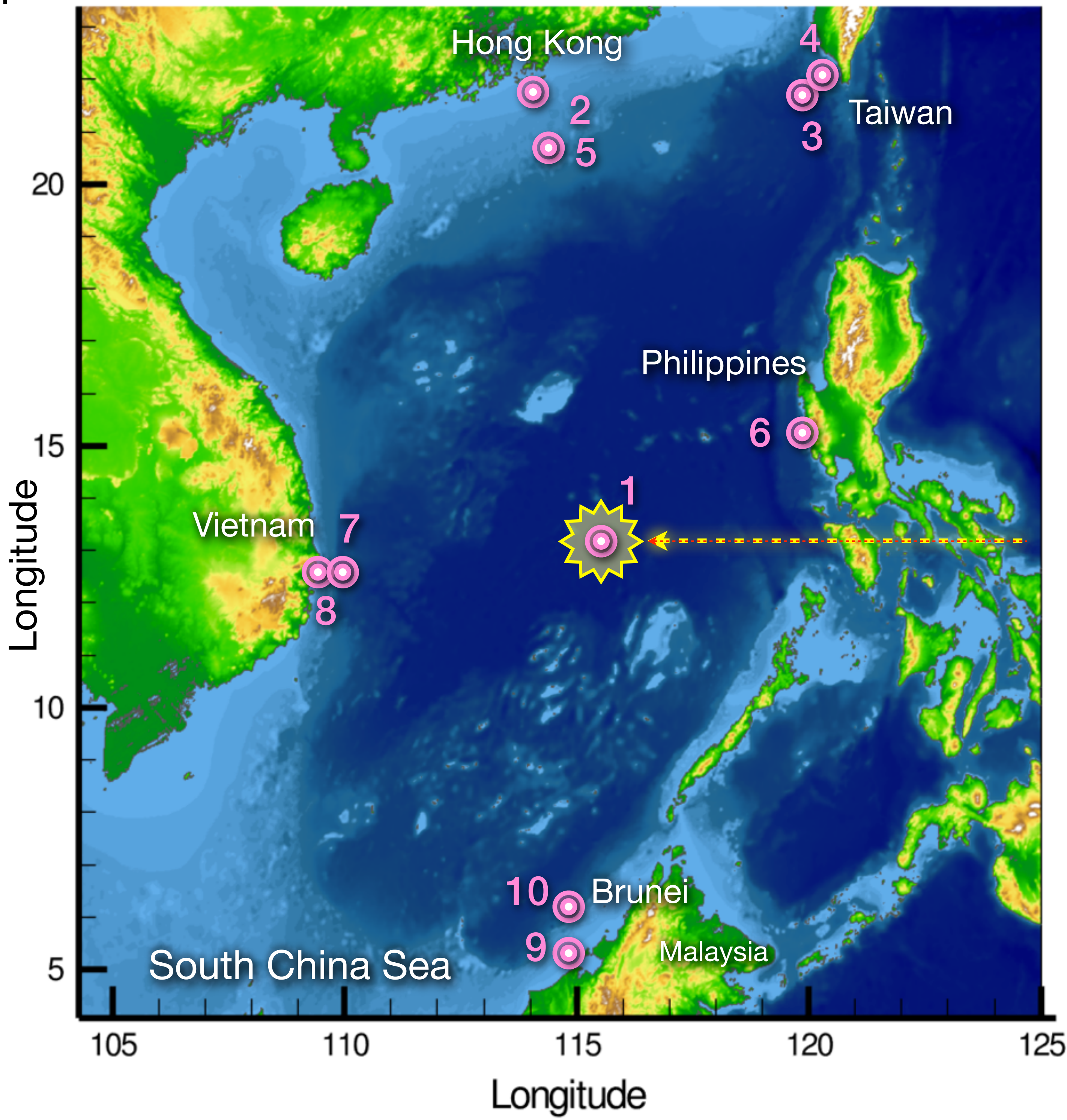


- Roughly circular footprint, roughly centered under location of peak energy release
- Peak overpressure reaches nearly 84 x sea level ambient pressure (84 bar)
- Peak is narrow, however lethal radius (4 psi ≈ 26.7% overpressure) extends 80-90km from ground zero, over 28,000 km^2 (!)

Tsunami Simulation

Instrumentation

- Measure wave height & velocity with "gauges" at 9 locations, (◎)
- Include deep water, narrow shelf, and broad shelf locations
- Depth near peak energy release is ~4.3 km



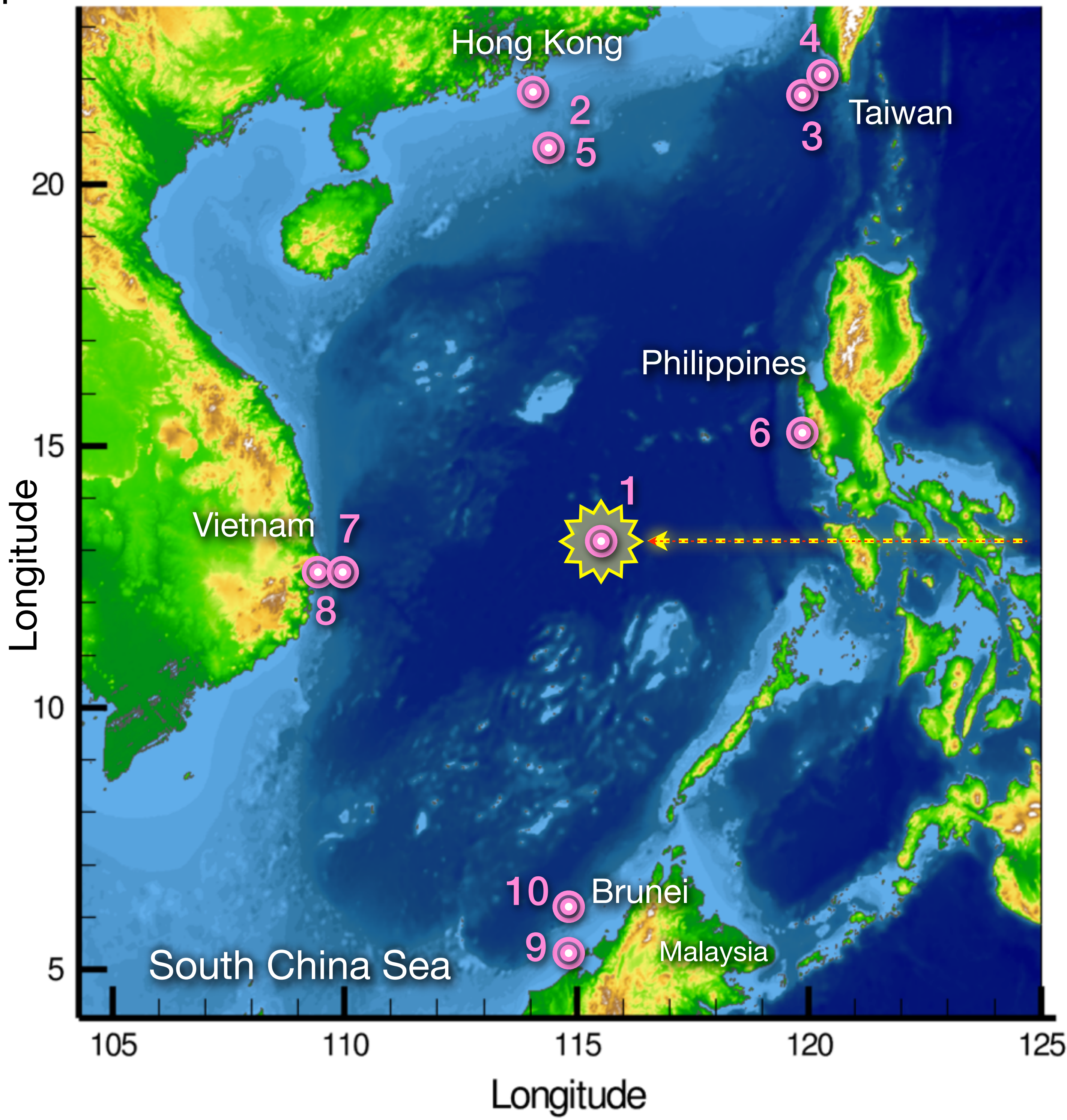
Tsunami Simulation

Instrumentation

- Measure wave height & velocity with “gauges” at 9 locations, (◎)
- Include deep water, narrow shelf, and broad shelf locations
- Depth near peak energy release is ~4.3 km

GeoClaw Simulation

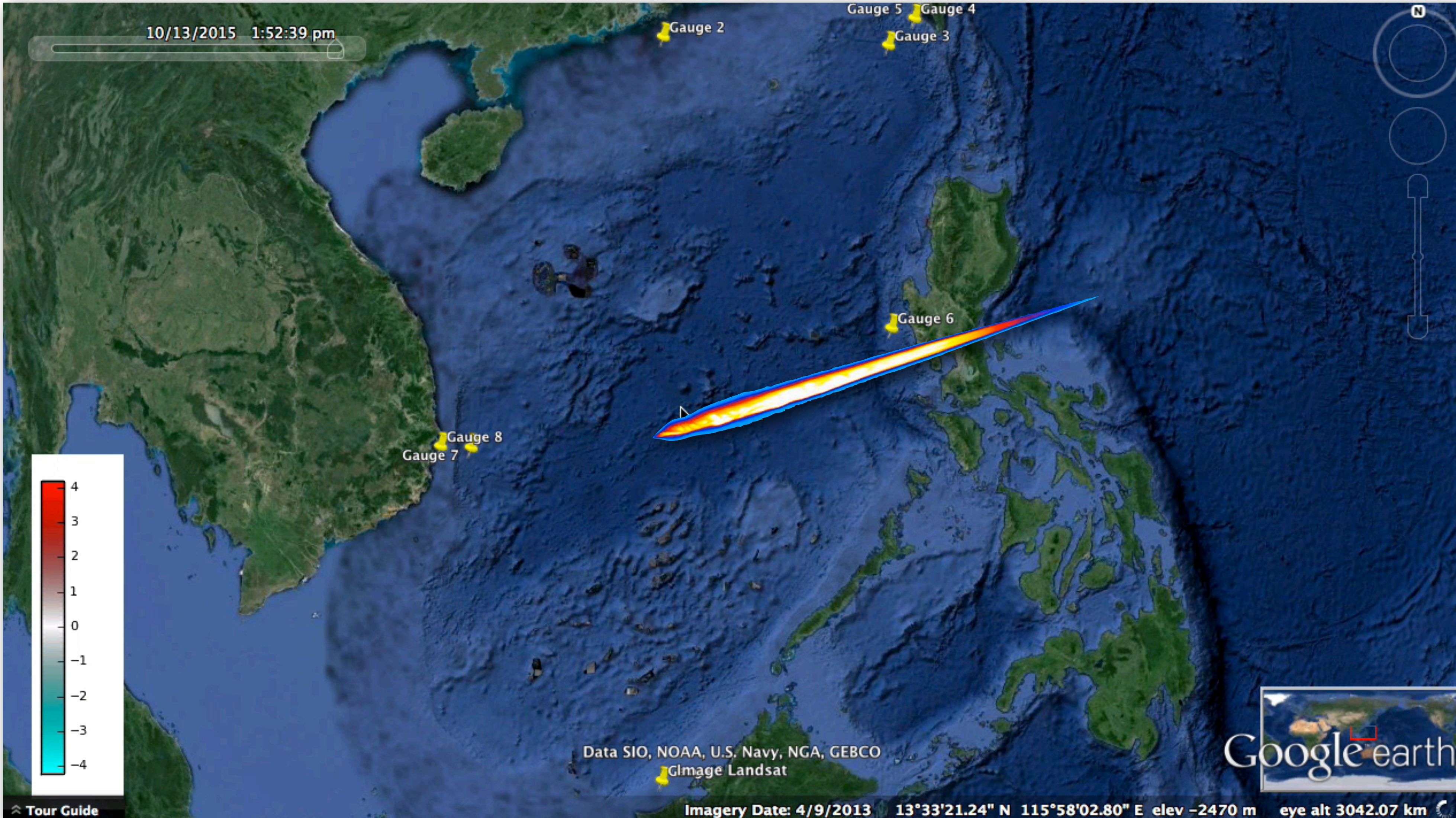
- Solve shallow-water equations using AMR for efficiency
- Simulations take ~800 core-hrs
- Time-dependent pressure from far-field propagation drives surface



Tsunami Simulation

(Preliminary)

D = 200m, V = 20km/sec, ϕ = 20°, ρ = 3300 kg/m^3, E_{Tot} = 662 MT tnt equiv.

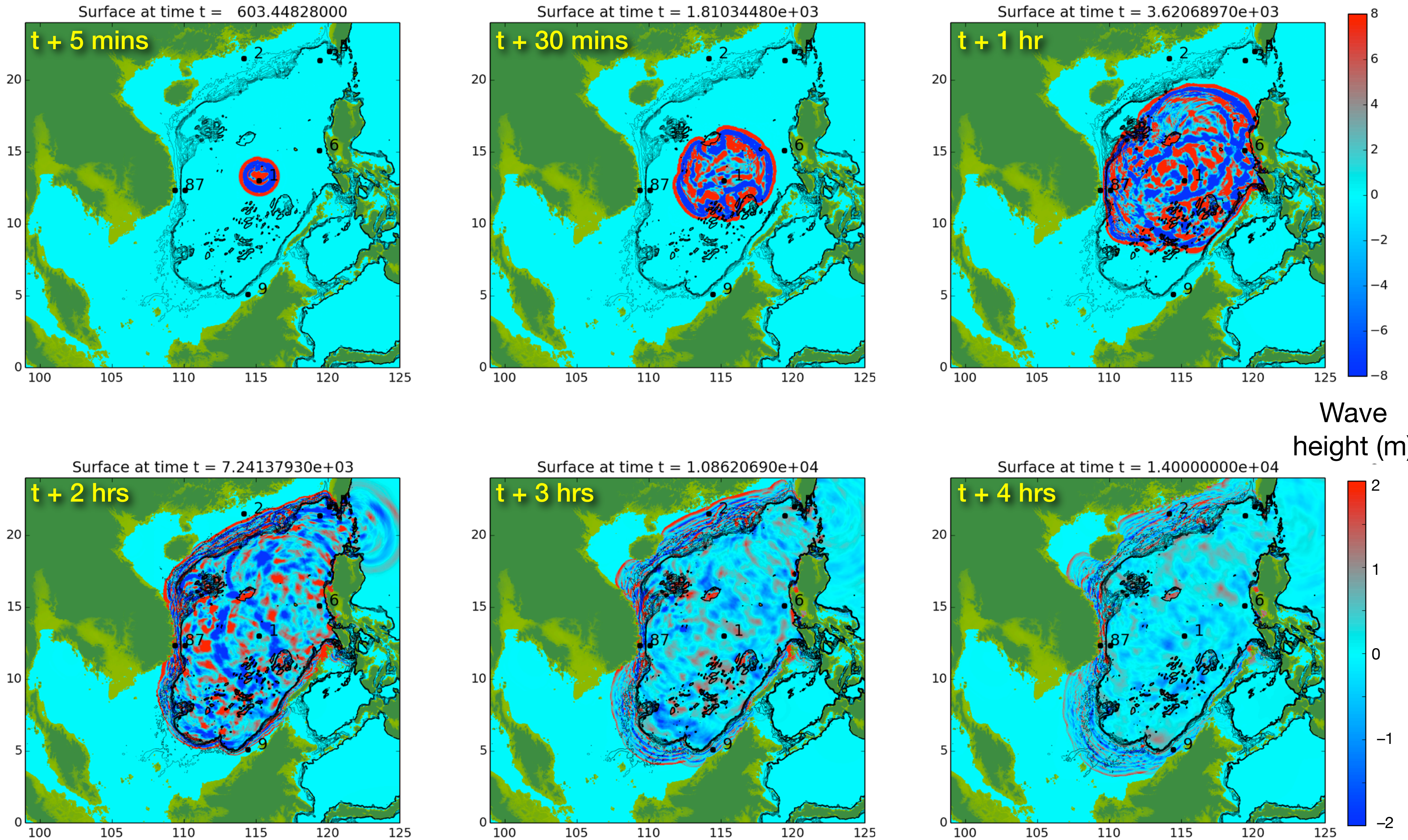


Tsunami Simulation

(Preliminary)

Water Surface 45 min After Entry

D = 200m, V = 20km/sec, ϕ = 20°, ρ = 3300 kg/m^3, E_{Tot} = 662 MT tnt equiv.

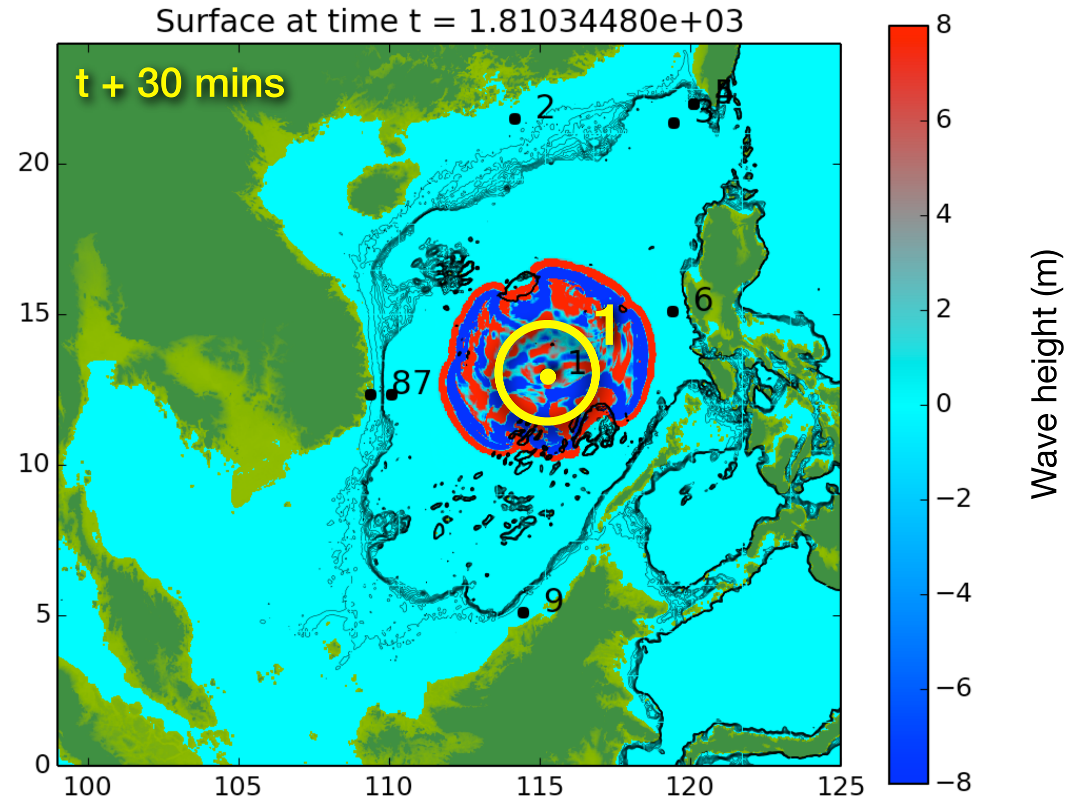


Tsunami Simulation

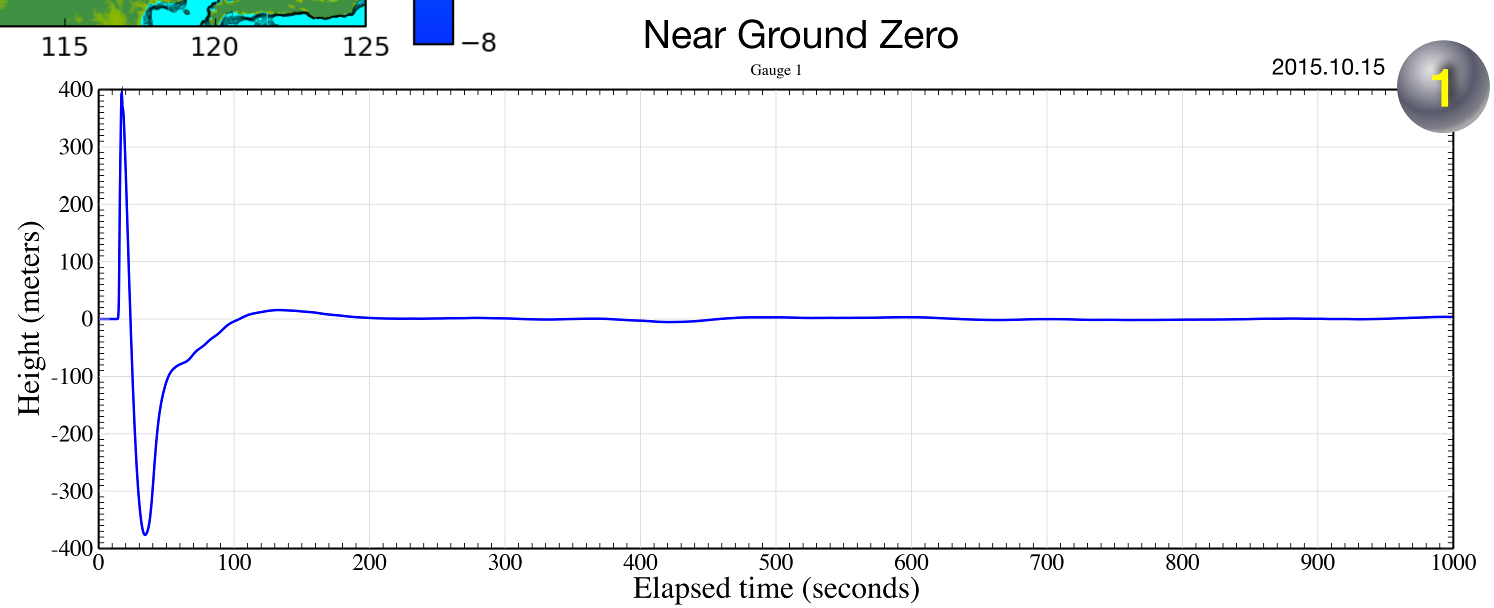
GeoClaw Simulation with adaptive mesh refinement

200m, 20km/sec, 20° entry, ρ = 3300 kg/m^3

(Preliminary)



- Over 100k adaptive AMR grid blocks track waves in simulations
- Energy release equiv. to Magnitude ~9.1 earthquake
- Surface overpressures greater than 84 x sea level pressure drives extremely high waves

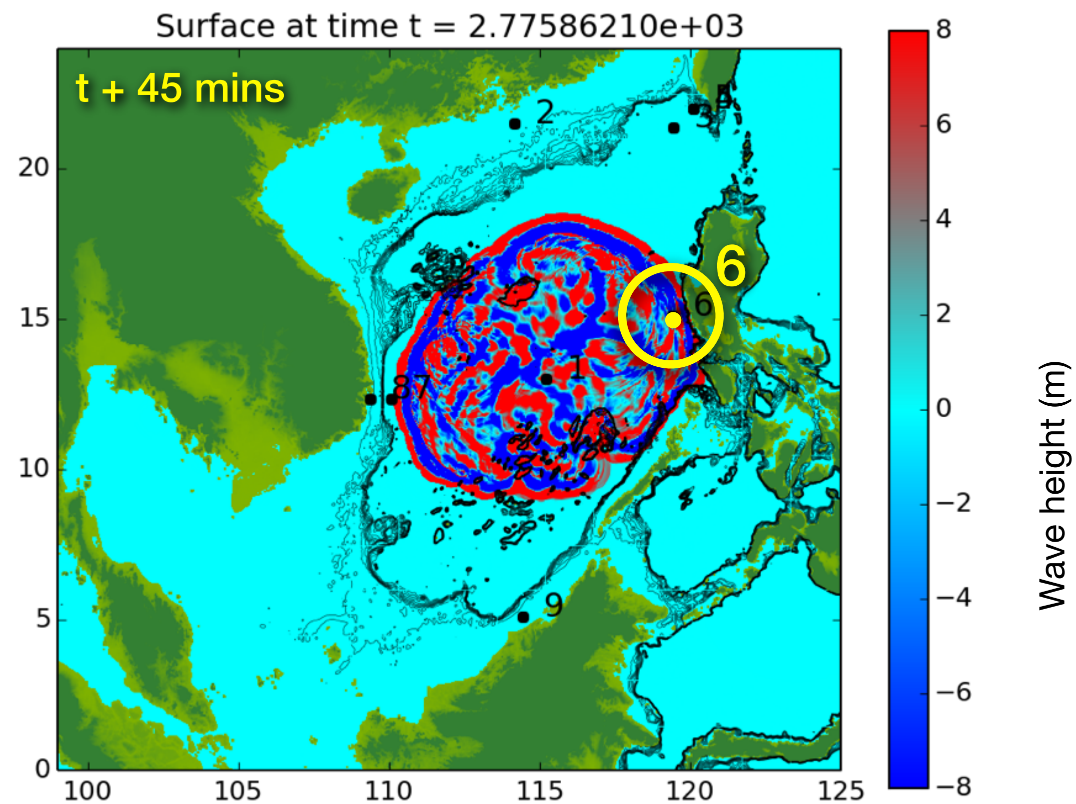


Tsunami Simulation

GeoClaw Simulation with adaptive mesh refinement

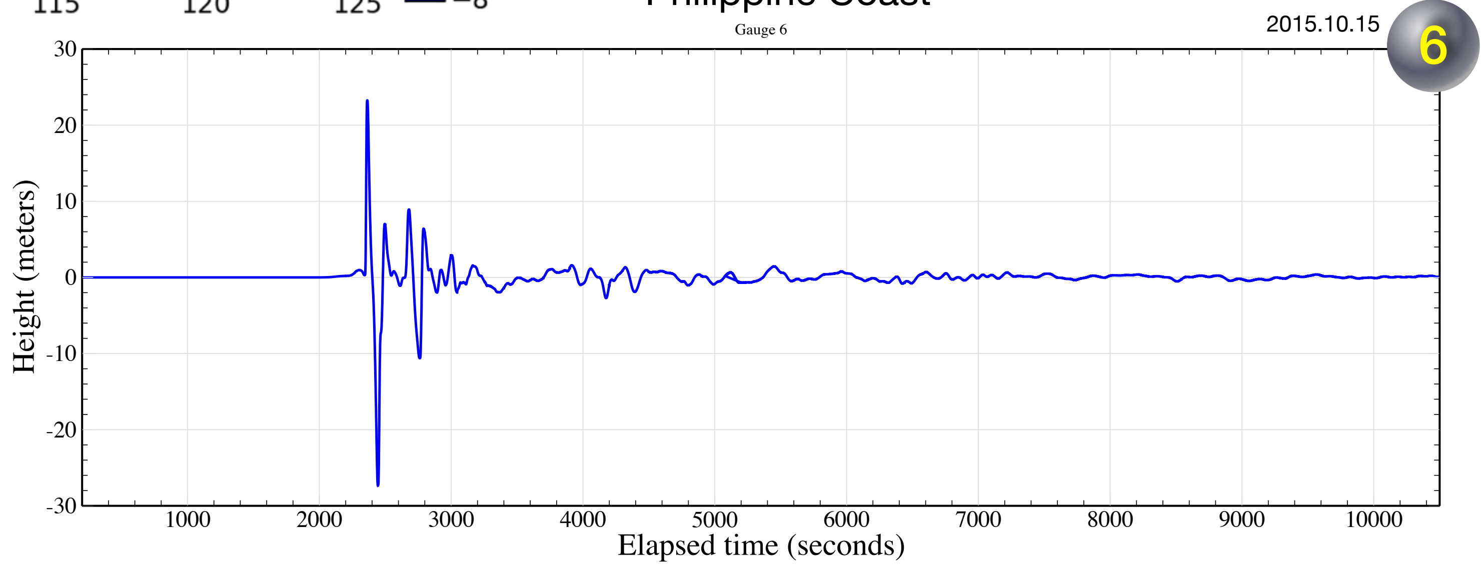
200m, 20km/sec, 20° entry, ρ = 3300 kg/m^3

(Preliminary)



- Waves arrive at Philippine coast ~40 min after airburst
- Very little protection and short propagation distance lead to largest waves observed at any of the coastal observation locations
- Peak-to-peak ~50m
- For reference, largest waves observed in Japan after 2011 M9.0 quake were up to 40m

Philippine Coast

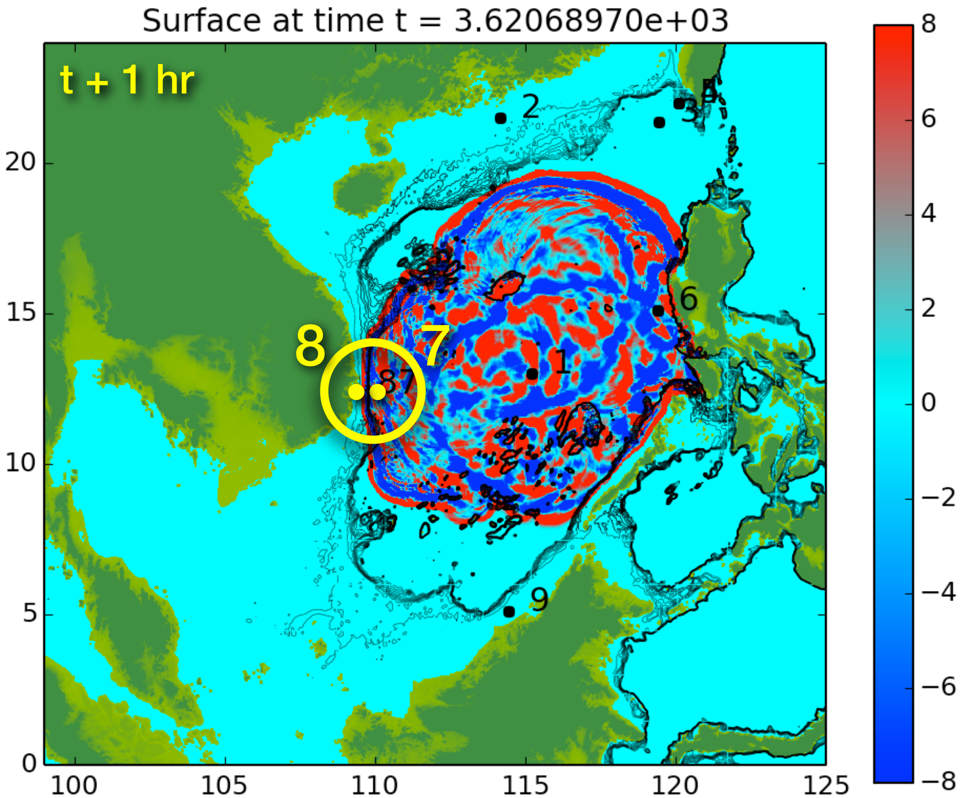


Tsunami Simulation

GeoClaw Simulation with adaptive mesh refinement

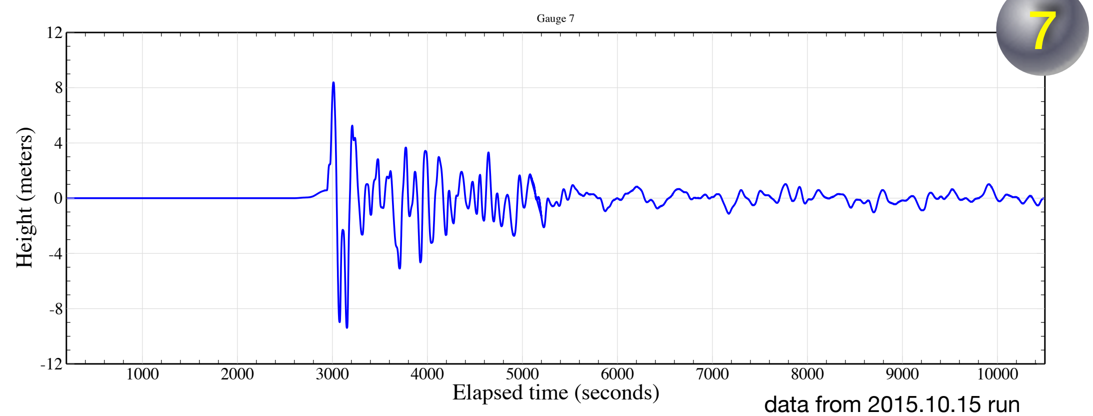
200m, 20km/sec, 20° entry, ρ = 3300 kg/m^3

(Preliminary)



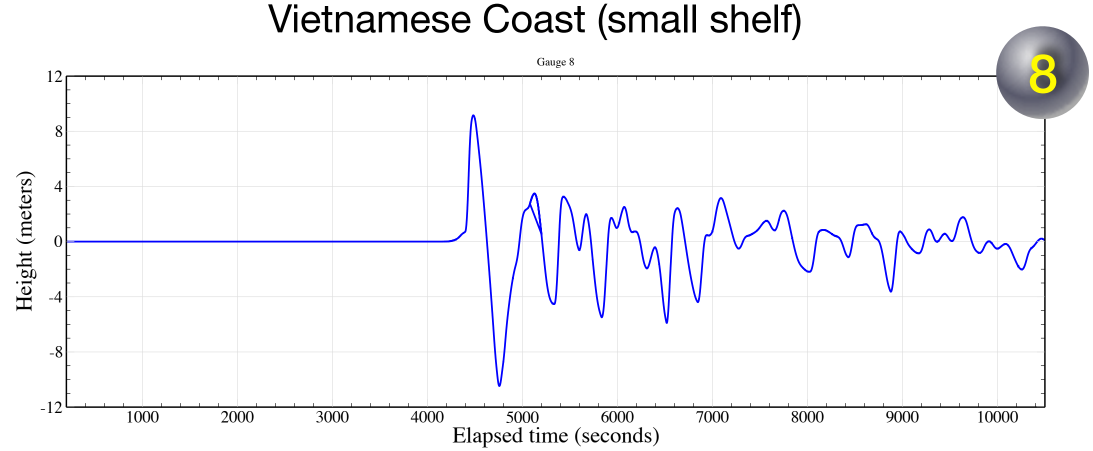
(contours from prev. (too big) run)

Vietnamese Coast (deep water)



data from 2015.10.15 run

Vietnamese Coast (small shelf)



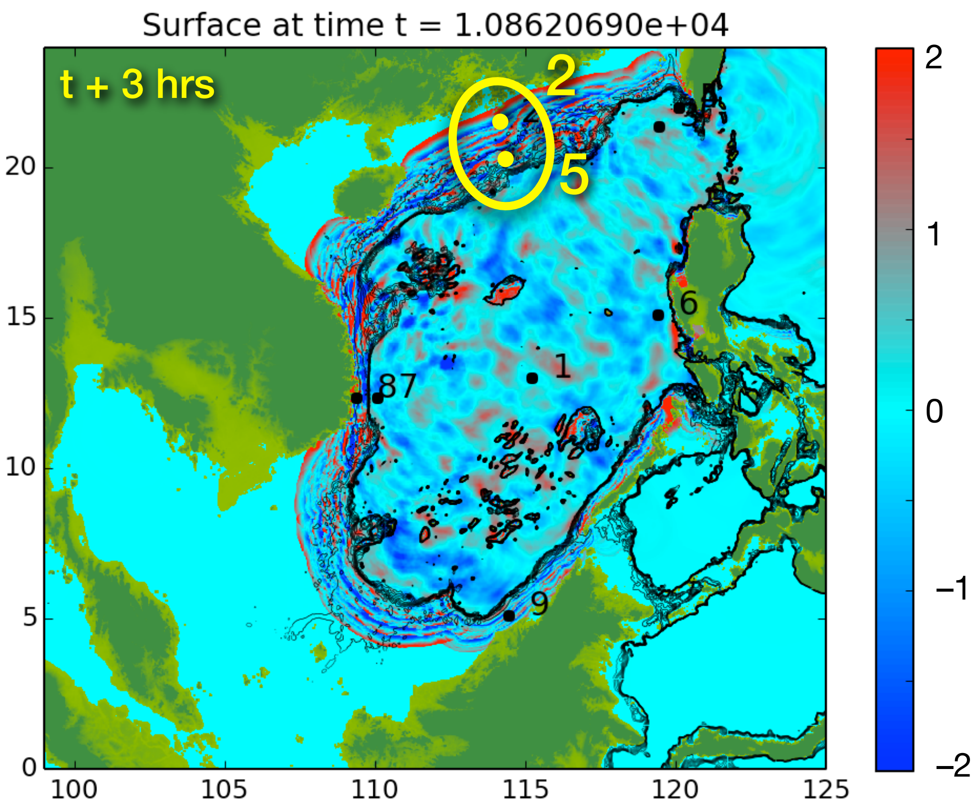
- Vietnamese coast strongly impacted, but longer running distance, and rough bottom bathymetry result in wave heights of 16-20m peak-to-peak
- Shoaling slow waves significantly as they approach the coast, observe a slight increase in amplitude

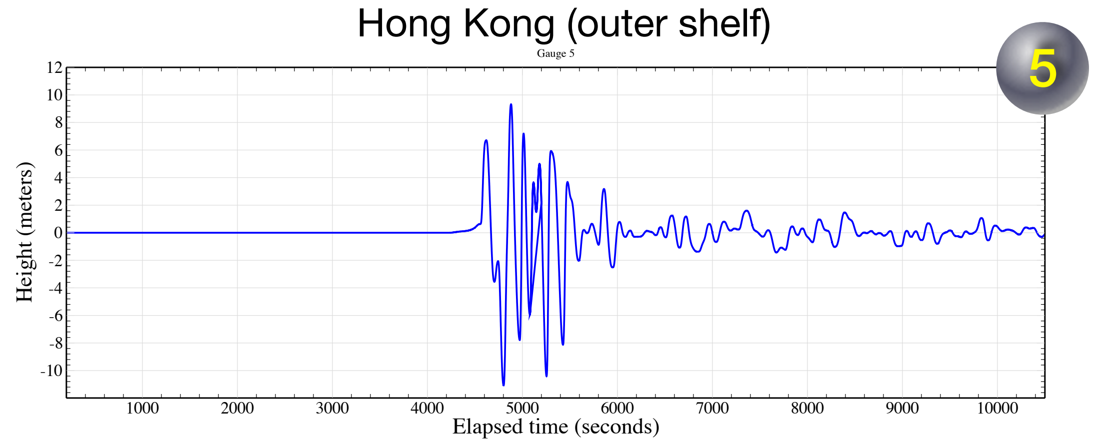
Tsunami Simulation

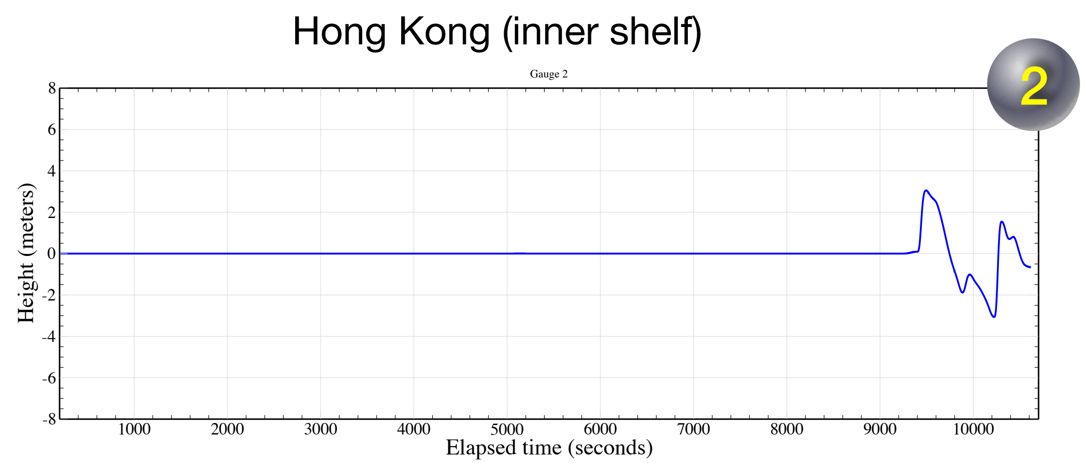
GeoClaw Simulation with adaptive mesh refinement

200m, 20km/sec, 20° entry, ρ = 3300 kg/m^3

(Preliminary)







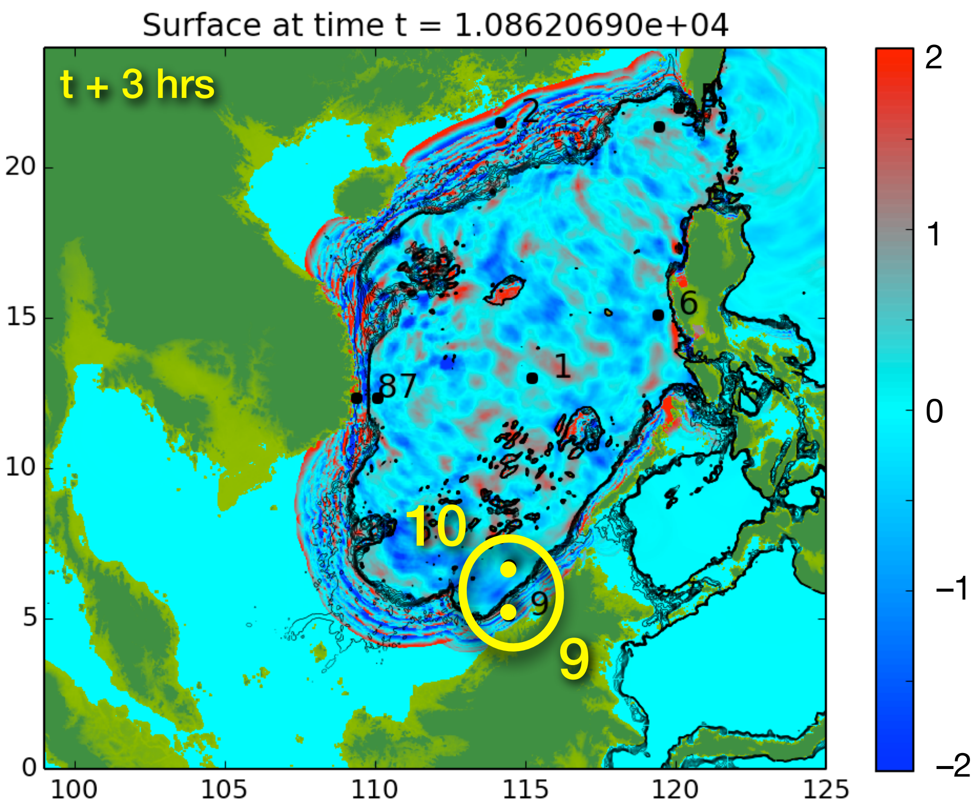
- Outer shelf is similar to Vietnamese coast, but coastline itself is strongly protected by broad shelf
- ~20m offshore waves reduced to ~6m peak-to-peak near Hong Kong harbor
- Very shallow broad shelf slows waves significantly over final hundred

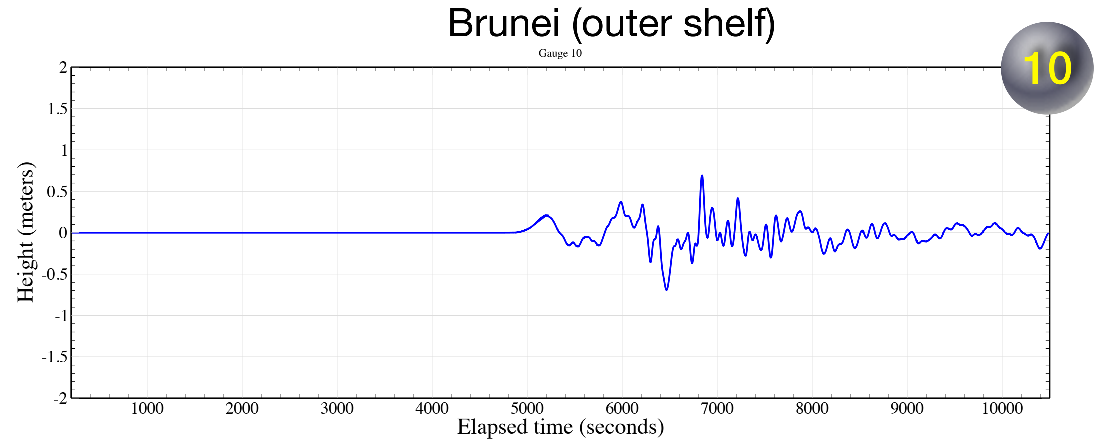
Tsunami Simulation

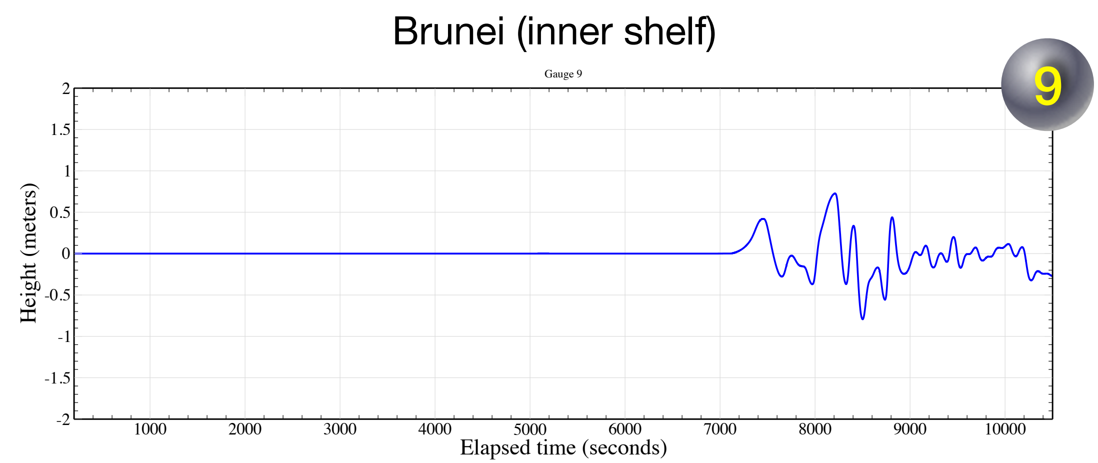
GeoClaw Simulation with adaptive mesh refinement

200m, 20km/sec, 20° entry, ρ = 3300 kg/m^3

(Preliminary)



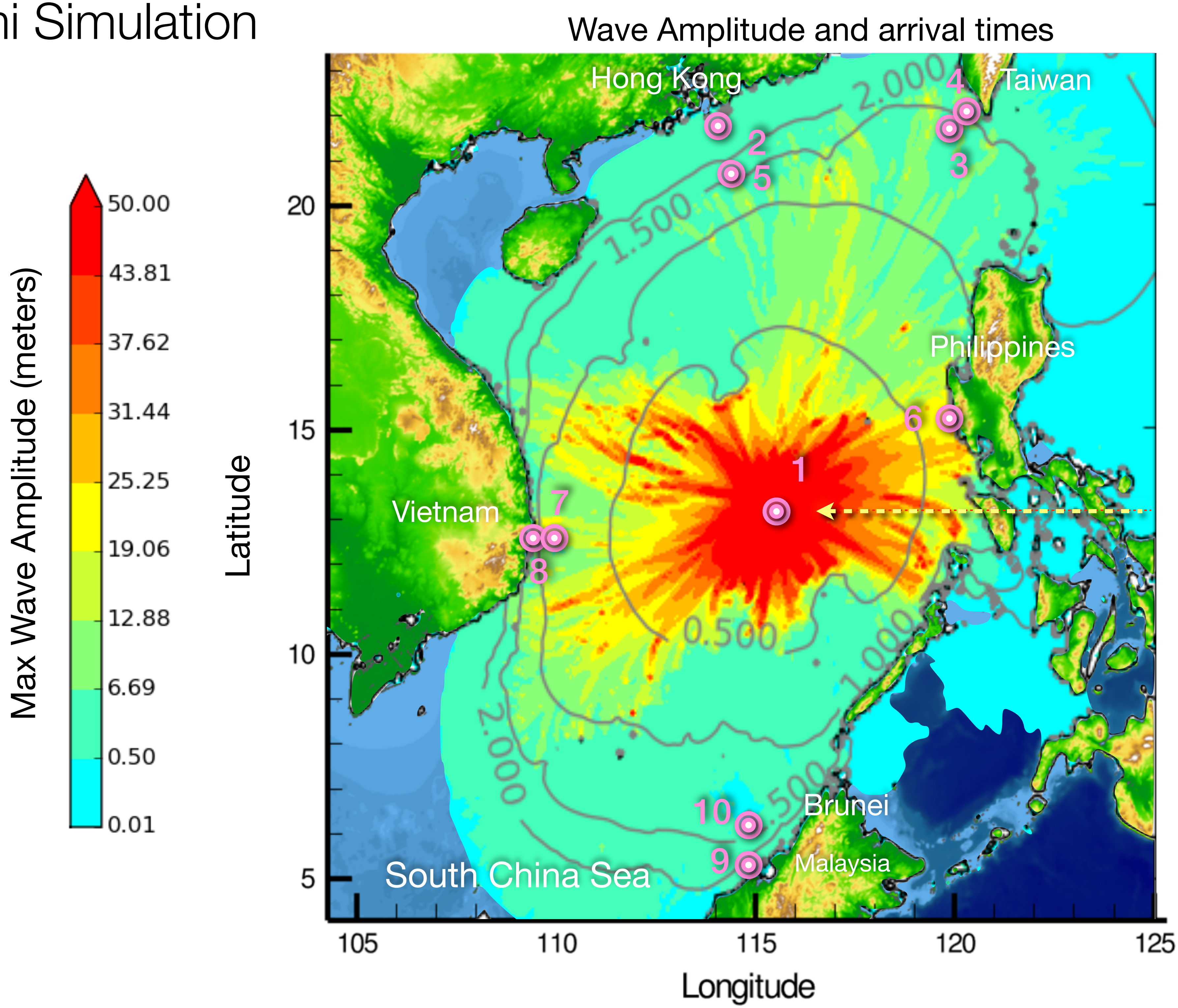




- Rough bathymetry with slow propagation speeds reduce wave heights significantly to the south
- Even with shoaling, observed wave heights have amplitudes of < 1m as they approach the coast

Tsunami Simulation

(Preliminary)



Summary

Atmospheric propagation and ground effects modeling

- Outlined modeling for far-field propagation of airburst events
  - Used conservation analysis to develop inputs from energy deposition
  - Uses energy deposition curve, detailed geometry not required
- Showed examples of verification and validation
  - Good prediction of magnitude and shape of Chelyabinsk ground footprint
  - Shock arrival times agree with observations to within seconds
- Preliminary sensitivity investigations (AIAA 2016-0998)
- Showed how we can extract envelopes and time-evolution of ground footprints for use in atmospheric-driven tsunami simulations

Next Steps...

Atmospheric propagation and ground effects modeling

- Parametric studies
  - Vary entry angle, size and strength of asteroid
  - Parametric modification of energy deposition curve
  - Feed to PRA to understand main risk drivers
- Tsunami prediction
  - Examine coupling Cart3D results with GeoClaw
  - 2016 Workshop on Asteroid-Generated Tsunami
- Cratering & splashing
- Terrain and structures

Thank You!

- NASA Advanced Supercomputing Division
- NAS Physics-Based Risk Assessment team
- NASA Ames Entry Systems Division – Task 2 team
- NASA ATAP Leadership
- ATAP Seminar Speakers
- NASA NEO Office

Questions?